Pitch drift in 'a cappella' choral singing

Thesis

Pitch Drift in *A Cappella* Choral Singing

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Abstract

Choral singing is a very popular activity in the United Kingdom (UK) with an estimated 2.14 million people, most of whom are likely to be amateur singers, regularly taking part in ensemble singing in over 40,000 choirs across the country. Despite the popularity of choral singing, most of the research into pitch drift (i.e. any difference between the pitch of the initial and final pitch of chords of the song) when performing unaccompanied (*a cappella*) choral music has concentrated on the internal effects of the music rather than external influences on the ensemble of singers.

Whilst singing regularly in amateur choirs for the past thirty years the author had observed that the performances of *a cappella* works varied considerably from rehearsal to rehearsal with respect to the degree to which the pitch drifted. At some rehearsals the pitch drift would be insignificant, at others it would be intolerable.

This thesis opens with an introduction to the research question and background theory. This is followed by a review of the academic literature on choral singing. The results of an international survey of choral practitioners plus a series of interviews and correspondence with professional musicians and composers will be presented. The outcomes of this survey informed the development of a subsequent series of experiments. These experiments were implemented to determine the effects specific external variables might have on the measured pitch drift of a cohort of eleven amateur choirs recruited to the research. These choirs performed and recorded the same two pieces of music at every rehearsal over an extended period. The data collected included:

- recordings of 192 rehearsal performances of each of two songs,
- the temperature, humidity and atmospheric pressure at each rehearsal,

- the attendance pattern of each singer over the period,
- an acoustic analysis of the rehearsal venues.

Additionally, every singer was invited to take part in a survey to determine their ability to discriminate between two closely spaced pitches.

The results from the measurements made from recordings of the *a cappella* performances confirm that the degree of pitch drift does vary irregularly from rehearsal to rehearsal. There was some variation between the choirs with several only drifting flat during performances whereas others tended to drift sharp on some occasions and flat on others. There was no correlation between the number of singers in each choir and the tendency to drift in pitch. Furthermore, choirs that auditioned their singers did not necessarily enjoy a lesser degree of pitch drift.

There was evidence from some choirs that the variation in attendance experienced at rehearsals may affect pitch drift. However, the changes in the environmental factors from rehearsal to rehearsal, such as temperature, humidity and barometric pressure, did not appear to be contributory factors to irregular pitch drift. Moreover, no correlation could be determined between the degree of pitch drift experienced by a choir and the acoustic parameters of their rehearsal space.

Whilst the pitch discrimination abilities of the singers taking part in the survey showed them to be no better or worse than those of the general population, an inconsistency in their responses between sharpened and flattened tones was discovered and has yet to be explained.

Acknowledgements

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A huge vote of thanks must go to musical directors of the eleven choirs who took part in the research and their singers (over 300 of them) who steadfastly put up with weeks and weeks of singing the same two songs, after all they did not have to do it. Additional thanks goes to those singers who shared their pitch discrimination abilities with me to benefit the research.

Grateful thanks goes to the Association of British Choral Directors (ABCD) for giving me the opportunity to publicise this research at their 28th Annual Conference, which was held in Oxford at the end of August 2013, and for space on their webpages.

Thanks are also due to the 216 choral practitioners who responded to the initial survey into pitch drift which was publicised by the ABCD, the Performance Studies Network (Perf-Stud-Net) e-forum, the Musicology-All e-forum and on the OU Life Intranet.

I am deeply indebted to Ralph Allwood, MBE; James Davey; Paul Edwards; Professor David Howard; John Rutter, CBE and Bill Strang, for giving their valuable time to provide me with their insightful comments and suggestions as to the causes of, and cures for, pitch drift.

I am additionally grateful to David Howard for access to his published and unpublished work on predictive pitch drift analysis, and permission to use his charts and diagrams.

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Seaton, R., Sharp, D. and Pim, D. (2014) 'Pitch drift in *a cappella* choral singing: the outcomes of an international survey', *Institute of Acoustics 40th Anniversary Conference*, 15–16 October, Birmingham, UK pp. 312–319.

Seaton, R., Sharp, D., Jones, A. and Pim, D. (2016) 'Experiments with Choirs – Practice and Pitfalls' *Acoustics 2016*, 5–6 September, Chesford Grange, Kenilworth, Warwickshire, pp. 362–373.

Audio CD track list

Track	Title (Rehearsals)	Time	Notes
1	Choir A Test Piece (18)	0:50	No attendance data for the first 5 rehearsals
2	Choir A Chosen Song (18)	0:59	No attendance data for the first 5 rehearsals
3	Choir B Test Piece (20)	1:04	
4	Choir B Chosen Song (20)	1:07	
5	Choir C Test Piece (17)	0:54	
6	Choir C Chosen Song (17)	1:23	First sample in the key of D major the remainder in D♭ major
7	Choir D Test Piece (20)	1:19	
8	Choir D Chosen Song (20)	1:24	Key change from A♭ major to B♭ major approximately half way through the piece
9	Choir E Test Piece (20)	1:09	
10	Choir E Chosen Song (20)	1:02	
11	Choir F Test Piece (20)	1:13	
12	Choir F Chosen Song (20)	1:10	
13	Choir G Test Piece (19)	1:14	
14	Choir G Chosen Song (19)	1:07	
15	Choir H Test Piece (20)	1:13	
16	Choir H Chosen Song (20)	1:12	
17	Choir I Test Piece (18)	0:57	
18	Choir I Chosen Song (18)	1:49	Three samples were necessary from each rehearsal due to the composition of the chosen piece
19	Choir J Test Piece (12)	0:52	
20	Choir J Chosen Song (12)	0:47	
21	Choir K Test Piece (12)	0:46	
22	Choir K Chosen Song (12)	0:49	Key change from A♭ major to B♭ major approximately half way through the piece
23	Test Piece for SATB	0:36	Synthesized grand piano
24	Test Piece for TLBB	0:44	Synthesized chorus

Glossary of terms

The following terms will be used in the physical and musical discussions within this thesis:

Amplitude (sound): related to the volume, intensity or loudness of sounds. It is the instantaneous magnitude of an oscillating quantity (e.g. a *sine wave*) often expressed in *decibels* if referred to the *threshold of hearing*.

Cent (music): 1/1200th of *an octave*. Also 1/100th of a *semitone* in equal *temperament* tuning.

Chord (music): two or more musical *notes* sounded together.

Consonance (or concord): a complete and stable quality of an *interval* or *chord.*

Decibel (dB): a ratio of powers. In sound an absolute (measured) value compared to a fixed standard value (the *threshold of hearing*) on a logarithmic scale. It is a convenient unit as the human ear responds logarithmically to sounds.

Dissonance (or discord): a quality of tension produced by a clash of *notes* in an *interval* or *chord*

Formant: *resonances* in the vocal tract which determine vowel quality and the *timbre* of an individual's voice.

Frequency: a measure of the number of repeating cycles in a *sine wave* or other repeating quantity in one second. The unit is the Hertz (Hz).

Fundamental Frequency: a periodic sound wave is usually made up from a number of (harmonically related) *frequency* components; the number of repeating cycles per second in a complex periodic sound wave is the fundamental frequency (f_0).

Harmonic: one of a series of *frequencies* each of which is a positive *integer* multiple of the original or first harmonic which is also the *fundamental frequency*.

Integer: a whole number which may be positive or negative.

Interval (music): the distance in *pitch* between two musical *notes*.

Molecule: the smallest particle of a substance that exists independently; the Earth's atmosphere contains largely of a combination in varying amounts of molecules of nitrogen, oxygen and (increasingly) carbon dioxide.

Note (music): a single musical sound that has pitch and duration or a symbol which represents this note.

Octave: an *interval* of eight *notes* which appears to be universally accepted in all cultures as being the most *consonant*. Sine waves with pitches an octave apart have *frequencies* in the ratio of 2:1, i.e. the higher pitch has a frequency that is double that of the lower pitch. Alternatively, the lower pitch has a frequency which is half that of the octave above it.

Partials: the *frequency* components that make up a complex sound such as the human voice. They are numbered such that f_0 is termed the first partial, f_1 the second partial, etc. Partials may be but are not necessarily *harmonically* related.

Pascal: the derived international unit of pressure. The unit of measurement of atmospheric pressure is the hectopascal (hPa), which is numerically equivalent to the imperial measurement of pressure the millibar.

Pitch (music): the subjective property of a musical sound which is heard to change when the *frequency* is changed whilst the amplitude is held constant. Musical pitches exist at fixed steps on a scale where they are referred to as *notes*.

Pure intervals: ratios of *pitches* formed from small positive *integers*, (e.g. 2:1 octave; 3:2 prefect fifth; 4:3 perfect fourth; 5:4 major third and 6:5 minor third.)

Resonance (sound): the reinforcement of musical sounds at specific *frequencies* due to the physical characteristics of the system involved with the sound.

Reverberation: the prolongation of a sound after it has been generated due to the acoustic properties of the enclosed space. The time taken for the sound in the enclosed space to decay by 60 dB is known as the reverberation time (RT_{60}).

Root (music): the *note* on which a *chord* is constructed. The *chord* is referenced by the name of the root *note*.

SATB: shorthand for sopranos, altos, tenors and basses – the four singing parts which comprise a typical mixed choir or chorus.

Schroeder Decay Curve: shows the total amount of energy remaining at any time following an impulse in a room. Useful for estimating the *reverberation* time (RT_{60}).

Semitone: equal to half a *tone*, it is the smallest *interval* in traditional Western music.

Sine wave (acoustics): a pure *sound wave* that includes only one *frequency* (f_0).

Speed (of sound): the velocity of sound in the medium. To a good approximation, in air the speed of sound can be taken as 344 m s^{-1} at 20°C.

Sound pressure level: the *amplitude* of a *sound wave* relative to the *threshold of hearing* expressed in *decibels*.

Sound wave: the means of propagation of a sound through a medium such as air.

Temperament (music): a method of dividing an *octave* into discrete tones. 'Equal temperament' and 'Just intonation' are two examples used in Western music.

Threshold of hearing: the minimum sound level of a pure tone that can be heard by the average human ear with normal hearing with no other sound present. A sound pressure of 20 micropascals (i.e. 0 dB SPL) with an air pressure of 1 atmosphere at 25°C. This level corresponds to the quietest sound a young person with undamaged hearing can detect at a frequency of 1,000 Hz.

Timbre: the sound quality of a musical *note* which is related to its harmonic structure. When produced by an instrument (including the human voice) distinguishes it from another instrument. (e.g. a violin from a trombone)

Tone: (i) a 'pure tone' (e.g. a *sine wave*) consists of a fundamental *frequency* with no *harmonics*. (ii) a 'musical tone' is characterised by *pitch*, *duration*, *intensity* and *timbre*. (iii) a 'whole tone' is an interval of two *semitones*.

Tonic (music): The reference *pitch* on which the other pitches of a musical composition are based.

Transducer: a device for converting one form of energy to another, e.g. a loudspeaker converts electrical energy to sound energy which can be heard.

Tuning (music): adjusting the *pitch* of an instrument (including the voice) to the system of *temperament* in use.

Vibration (sound generation): means by which musical sounds are generated due to controlled periodic movement of a string (e.g. violin), air in a tube (e.g. pipe-organ), or to and fro movement (e.g. electrical loudspeaker). The number of vibrations in a second (i.e. the repetition rate) determines the *pitch.*

Wavelength: the distance a sound wave travels within a medium between repeats of a cyclic wave. It is inversely proportional to the rate of *vibration* of the propagating sound, measured in metres. For a fixed *frequency* the wavelength is dependent on the *speed of sound*.

Chapter 1
Introduction to choirs

> 'Singing in a choir is one of the most rewarding group activities…it provides an opportunity to bring music to others, enriching singers and audiences everywhere.' (David M. Howard, 2015).

1.1 Introduction

I was singing in a regular weekly choir rehearsal with an amateur choir in the South of England. We had just finished an unaccompanied song and the musical director was berating us for dropping in pitch.

> 'You kept pitch very well last week; this week was dreadful!' (or words to that effect).

This was neither the first time nor the only musical director from whom I had heard these words. It made me wonder what was different about last week? Could it be humidity, or maybe the temperature in the rehearsal venue? And then I realised I'd not been at the previous week's rehearsal…

This research intends to pursue reasons why choirs are not able always to maintain the pitch when they are performing the same *a cappella*[1] music on a regular basis, such as in the above example. Performances sung *a cappella* require no instrumental accompaniment or occur when the accompaniment is removed for musical effect and then, at some time later, reintroduced. In the case of unaccompanied choral singing, the drift from the intended pitch

[1] *A cappella*, from the Latin, is the Italian for 'in the manner of the chapel' and now refers to choral music intended to be performed without instrumental accompaniment.

may not be so obvious to the listeners other than to those with knowledge of, and the ability to recognize, the pitch. In the case of the latter, however, the reintroduction of instrumental accompaniment may make any drift in pitch very obvious indeed!

The *a cappella* music referred to throughout this thesis is that sung throughout the Occident, i.e. Europe, Australasia and the Americas. It embodies a wide range of musical genres that will be explained further in the discussion of the repertoire of choirs in Section 4.3.2.

1.2 The popularity of choral singing

Choral singing is a very popular activity and pass-time. An estimated 37 million people regularly take part in collective singing in over a million choirs across the European Continent (i.e. the EU28 plus Russia). This represents around 4.5% of the European population according to a survey *Singing Europe* undertaken by the European Choral Association[2] in 2015. They reported that Austria had the largest proportion of singers at 11% per head of their population with the United Kingdom having just 3.3%. A 2017 survey of choral singing in the United Kingdom by Voices Now[3] estimated that 2.14 million people regularly sing in one or more of over 40,000 choirs, with numbers of singers ranging from 4 to 700. Choir members range in age from 6 years to over 100 years old and are from all backgrounds. The survey found fourteen different musical genres were sung, ranging from Early music to Samba, with Modern Contemporary being the most popular. There was no indication as to the extent that unaccompanied (*a cappella*) music was performed.

[2] www.singingeurope.com (Accessed 16 January 2018)
[3] voicesnow.org.uk (Accessed 8 July 2018)

1.3 Scope, methodology and outline

1.3.1 The scope of this research

In looking for causes of pitch drift, the music alone could be studied, that is to say the ways in which it is composed, including the words or sounds used. This could be considered to be an internal approach involving factors such as chord progression and keys along with melodic considerations including line, movement and contour. However, there may also be factors external to the composition, which could include the numbers or attendance of singers and the balance of the parts, environment within the performance venue or the time of day. It is the second, the external factors, that have been chosen for investigation in this research. The reason for making this choice was that, from experience of some thirty years of choral singing, it has become apparent that the drift in pitch in singing a particular work at one rehearsal differed noticeably from that at another. Should the pitch drift be due to internal causes alone one would expect it to be consistent at each rehearsal. It is this variability of pitch drift between rehearsals that seems so intriguing and unaccountable. Whilst this does not dispose of the possibility of internal causes of pitch drift, it does suggest that there are external factors which introduce sufficient variability to allow study of pitch drift detached from the composition of the music.

1.3.2 The method of study

In taking an externalist approach to this research, it was necessary to take the research methods outside the safe confines of the university campus to the singers who may well be experiencing the problems with pitch drift similar to those described in the opening of this chapter. A more controlled approach, whereby a small and generally select group of singers and or solo singers have been involved in specific areas of research involving pitch drift, is far more common and will be discussed in Chapter 3. There is little evidence of any research work on pitch involving a number of choirs. Further, whilst there is a wealth of anecdotal evidence of the pitch drifting flat rather than sharp, certainly with Western choral music, no research evidence could be discovered to suggest why this should be the case. The next section describes the research in terms of the chapters in this thesis.

1.3.3 Outline of this thesis

Chapter 2 first sets the scene with a brief history of choral singing. The main part of this chapter follows with an introduction to the background theory that informs the experiments which were undertaken by choirs over an extended period of time. This starts by looking at the way sound is carried through the air from a source such as a human voice to a receiver, the human ear. The way sounds vary, both in pitch (raised or lowered) and in amplitude (loud or soft), are discussed and the units used for pitch and amplitude are described. This is followed by an introduction to musical pitch and a discussion on the various tuning methods (temperaments) which are used. A discussion of the way the human ear converts sound waves into electrical impulses, which are subsequently decoded by the brain as sound, is followed by a description of how humans generate the vibrations necessary to make sounds including music. The chapter concludes with a brief overview of the way the acoustical properties of rooms are measured, by considering what happens when an impulsive noise (such as that provided by the bursting of a balloon) is introduced into a room.

Chapter 3 surveys the available academic literature relating to this research. The chapter opens with three descriptions of pitch drift: two from very respected choral musicians and a research paper describing the occurrence of pitch drift experienced by a choir when singing *Os Justi*, a motet by the Austrian composer Anton Bruckner (1824–96). Suggested causes of pitch drift in choirs are then discussed. These include the problems of hearing oneself in a choir, the acoustics of the room and environmental factors. Discriminating between pitches is covered, including certain people’s ability to recognise any pitch and to be able to reproduce the same without any external stimulus – the so-called 'absolute' or 'perfect' pitch phenomenon. The chapter concludes with a review of tuning in *a cappella* singing, which includes some up-to-date research into why humans appear to be able to pitch a note more accurately when they whistle it rather than when they sing it.

Chapter 4 introduces a survey in which a series of questions were put to choral practitioners regarding their experiences of pitch drift when either singing with or directing choirs. The questionnaire was in three parts: about your choir; about your rehearsals; and your experiences of and possible reasons for pitch drift. As stated earlier in this chapter, there is much anecdotal evidence of pitch drift, but it was felt important to get the experiences from a large number of choral singers, even though they were self-selected. It was hoped that at least one hundred replies would be received, and despite a slow start the overall response more than doubled expectations. A report of the interviews with four experienced choral conductors and two very well-regarded choral composers follows. The outcomes were used to inform the development of experiments to be undertaken with choirs.

A unique feature of this research is the involvement of several amateur choirs from around the United Kingdom in a series of experiments to gather data on how pitch drifts over a number of regular performances (at rehearsals of the same music at the same time of day). Chapter 5 introduces the development process and describes the rationale for each of the three experiments which were selected in part from the outcomes of the above survey. The three experiments were designed to study pitch drift at a particular rehearsal against: the attendance at that rehearsal; measurements of the environment at that rehearsal; and the pitch discrimination of the choir members (not rehearsal dependent). Two important considerations were that each experiment should cause minimal disruption to the choir’s rehearsal and that experiments would be run by the choir members themselves, based on the experience of the Open University in running experiments at a distance. This meant choir members could only expect to receive support by telephone and email, following an introductory meeting, except in extreme circumstances.

Chapter 6 reports on the results from the experiments. Following a discussion of the types of choirs involved in the experiments, the data collected at the rehearsals are introduced. A strategy to adjudicate on the pitch drift at each rehearsal is introduced and the rationale for using the methodology is discussed. On a choir by choir basis, the pitch drift results from each rehearsal are then correlated against the environment factors and the attendance register collected at each rehearsal. The analytical techniques used are described in detail and the results tabulated.

Chapter 7 discusses the results from the choirs. The thesis concludes with suggestions for areas of further research into why pitch drifts on an irregular basis when choirs rehearse, which may lead to a better sound in public performances, which should be the aim of every amateur choir.

Appendix 1 includes a list of common sound pressure levels described in Chapter 2. A copy of the survey of choral practitioners discussed in Chapter 4 is presented in Appendix 2, along with the trifold flier which advertised this research project in Appendix 3. The project plan for this research can be found in Appendix 4. Appendix 5 has a copy of the Experiment Handbook which accompanied the experiment kit developed in Chapter 5. Appendix 6 contains the specifications of the environment meter with the accompanying environmental data log sheet in Appendix 7. Appendix 8 contains two copies of the specially written *Test Piece* for SATB and TLBB choirs along with details of the chosen songs sung at rehearsals in Appendix 9. Appendix 10 details the post rehearsal questionnaire for completion by the choirs' musical directors. Appendix 11 describes the code used to generate the tones for the pitch discrimination survey and Appendix 12 contains a copy of the introductory letter to the survey. Appendix 13 has a copy of the experiment kit handover letter. Appendices 14 to

16 contain the results from the experimental data detailed in Chapter 6. Finally, a list of choirs that took part in the experiments described in Chapter 5 will be found in Appendix 17.

A CD ROM containing recordings used in the analysis of each choir's pitch drift and two synthesised recordings of the *Test Piece* (one with piano, the other with chorus effect) will be found inside the rear cover.

Chapter 2
History and theory

> 'There is geometry in the humming of the strings, there is music in the spacing of the spheres.' (attributed to Pythagoras, c. 450 BCE)

2.1 Introduction

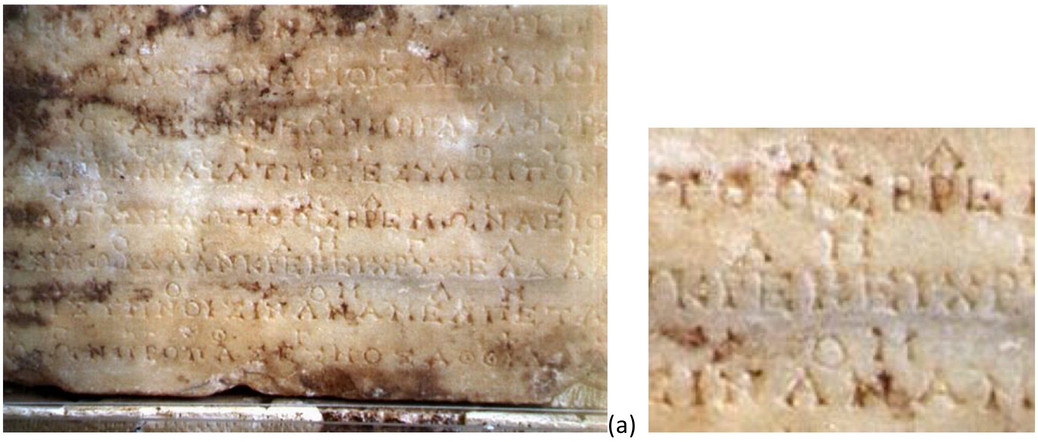
This chapter provides some background and theory covering the various physical factors that are involved in the process of singing. The theory that is described supports the chapters that follow, and any unfamiliar terms may be found in the Glossary.

2.2 A brief history of choral singing

Making music, and even more so appreciating it, is universal to all humankind and yet, whilst the evolutionary history of language has been studied and debated by linguists, psychologists, anthropologists, etc., with a few notable exceptions, nothing has been said about the origins of music. In his 1871 book *The Descent of Man* Charles Darwin devoted a few pages to the evolution of music, and towards the end of the last century John Blacking (1973) proffered the idea of music being an innate and universal human attribute. In his book *The Singing Neanderthals* Steven Mithen (2005) describes the development of music as arising from the 'grunts, barks, screams and hoots' with which early hominids communicated with each other. He concludes by defining language as a communication system specializing in the transmission of information whereas music specializes in the transmission of emotion. Furthermore, Mithen suggests that modern humans used language to communicate with each other, whilst music provided the means of communication with supernatural and religious entities.

The first evidence of musical instruments can be traced back over 40,000 years to a time when *Homo sapiens* had dispersed from their origins in central Africa to Australasia and Europe. Indeed, flutes and pipes made from bones of birds and mammoth tusks, discovered in caves at Geissenklösterle in Germany (Münzel et al., 2002), have been dated as being over 36,000 years old. As modern humans developed, percussion instruments made of clay, such as rudimentary xylophones, appeared. Eventually, metal would be used to construct instruments similar to brass gongs.

Amongst the earliest surviving works in the choral repertoire are two Delphic hymns which date to 128 BCE and were addressed to Apollo. Figure 2.1(a) is a photograph of the first hymn. The occasional symbols above the line of Greek text, illustrated in the detail of (b), are a form of music notation.



(a) (b)

Figure 2.1 (a) Photograph of the original stone at Delphi containing the first of the two hymns to Apollo; (b) a detail of the hymn illustrating the music notation above the text

There was an abundance of instrumental music and singing in early Christian worship. Psalm 150 (from the 1662 *Book of Common Prayer*) extolled worshipers to ‘Praise him upon the strings and pipe’ and ‘Let everything that hath breath: praise the Lord’, which suggests singing was also a form of praise well before the start of the Common Era. The *New Testament* of the Christian *Holy Bible* (Matthew 26 v. 30) refers to Jesus and his disciples singing a hymn at the Last Supper before going out to the Mount of Olives. However, singing in the early Christian Church was most likely to be in the form of chants performed by clerics, similar to those heard in today's Eastern Orthodox Church. This is evidenced from the way the texts were written down, there being no musical notation at this time. In 7th century Britain the Synod of Whitby (664 CE) set the rules of plainsong for the liturgy by following those specified in Rome (thanks to a visit from St. Augustine), which in time led to the establishment of the first musical notation. According to Gant (2015) the liturgy allowed preachers to find a particular pitch and resonance of their voice – thus, in effect, singing. He likens this to the orders given by a sergeant major on a parade-ground (e.g. Trooping the Colour on the Sovereign's birthday in London) whose voice has a rise and fall which can be notated in music. Resonances in the vocal tract (see sub-Section 2.3.6) cause natural amplification allowing a single voice to be heard above the noise from being out-of-doors in a city or in large indoor spaces.

Plainsong is a corpus of single-lined tunes each associated to a particular text in the liturgy. The compositions for the texts were based upon a series of scales or modes which were given names taken from the Ancient Greek (e.g. Phrygian and Dorian). The notation used 'neumes', i.e. note-heads without tails, which simply provided an indication as to whether the next pitch was above, below or the same as the present one. Originally written without any indication of tempo or staff-lines (horizontal lines which define the pitch of the note), this early notation offered no more than an *aide-mémoire* to the singer who would have learned the chant previously. Guido d'Arezzo (c.995-1050) added three or four staff-lines (Károli, 1979, p. 16) which are shown in Figure 2.2, a fragment of a plainsong chant from a 14th-century illuminated manuscript depicting neume notation. It was not until the 17th century that a stave of five lines became generally accepted as the standard used today.

Figure 2.2 An example of plainsong showing neumes from an early 14th-century English Missal, by Unknown - National Library of Wales, CC0, commons.wikimedia.org/w/index. php?curid=44768046

By the end of the first millennium, musicians had started experimenting with Gregorian plainsong (named after Pope Gregory 1 who introduced plainsong to the British Isles). They added musical lines to augment the simple chant, which required additional singers alongside the priest or monk who would normally sing the chant alone. This was the introduction of the polyphonic system which would dominate church music for the next seven centuries, and the foundation of the choir. The rules set by Rome regarding singing polyphonic music were very strict. Only one extra vocal line was allowed with the additional notes being sung at either the fourth or fifth above the original tune. Singers were trained to add the upper part at sight. Gradually these rules were relaxed; a drone (i.e. a single note) was allowed and more florid improvisation could be added. A third vocal line followed along with changes in rhythm – even between voice parts, making the sound so complex that complaints were made that the words and chant were lost.

Before the development of the printing press, books were handwritten and very expensive, so choristers would gather around a single large illuminated manuscript book (i.e. the score) mounted on a stand, shown in Figure 2.3. Following the development of printing in Germany in the mid-1450s, copies of scores became more readily available and spread widely across Europe during the Renaissance.

Figure 2.3 Singing from a single manuscript book

Polyphonic sacred music, consisting mainly of masses and motets sung *a cappella*, was the principal form of notated music during the Renaissance period. However, the Renaissance also saw the development of secular choral music such as madrigals and part-songs, sung mainly unaccompanied by between three and six voice-parts (von Fischer et al., 2001). Originating in Italy these songs were often highly ornamented musical settings of love-poems and stories from mythology, but later and in England included tributes to the first Queen Elizabeth.

The period following the Renaissance saw an expansion in the number of singers in choirs which was necessary given the size of the orchestral accompaniment. The *Norwich Gazette*[1] reported in October 1727:

> '... there was a Rehearsal of the Coronation Anthem in Westminster-Abby, set to musick by the famous Mr Hendall: there being 40 voices, and about 160 violins, Trumpets, Hautboys, Kettle-Drums and Bass...'

[1] en.wikipedia.org/wiki/Choir (accessed 12 July 2018)

Towards the end of the 18th century, large-scale works were composed, often suitable only for prestigious ceremonial occasions. However, they found favour with amateur choruses who, having started as social groups, became choral societies with memberships of over a hundred singers and so able to support larger works. Smaller groups known as chamber choirs were also supported by compositions from composers who provided motets and part-songs which required little or no musical accompaniment.

Today's choral singers, who may join many types of choir as may be seen in Chapter 4, are able to take advantage of the wealth of choral repertoire from the past. They also enjoy new music either from private commissions or as a result of sponsorship from large organisations and public competitions.

2.3 Background theory

2.3.1 Preface

Sub-Section 2.3.2 describes how sound travels through the earth's atmosphere as waves which are generated by some form of transducer generating vibrations in the air. The degree of displacement of the air molecules determines how loud we perceive the sound to be. The measurement of sound levels, the subject of sub-Section 2.3.3, is important for ensuring, for example, that audio recordings are free from distortion which might affect the judgement of any pitch drift which might be present. This section also introduces the decibel, the standard unit for sound level measurement. Sub-Section 2.3.4 discusses the method of determining pitch in Western music, which is central to this research. It describes the relationship of cents to semitones and of semitones to named musical notes. A description of the mechanism of the human ear is given in sub-Section 2.3.5 with particular reference to the perception of musical tones and intervals. The subject of how hearing changes over time as we age is also covered. The way the human voice is controlled in sub-Section 2.3.6, with particular reference to the parts of the body that produce the required sound in terms of frequency and timbre. Finally, in sub-Section 2.3.7 the acoustical properties of venues in which choirs rehearse are considered.

2.3.2 Sound waves

When a sound source, such as the human vocal folds or an electric loudspeaker, starts to vibrate it generates waves of compressions and rarefactions in the air (Figure 2.4) which causes our eardrums to vibrate in sympathy if we are in within earshot of the source (sub-Section 2.3.5). Air is a gas consisting of evenly distributed molecules, which if disturbed (i.e. compressed or expanded) due to a source of vibration, passes the disturbance away from the source. The air as a body is not moved in conveying sound (Beament, 2005, p.4) so very little energy is expended as a sound wave propagates, allowing sounds to travel over considerable distances as long as there are no objects to deflect them, becoming gradually weaker until they are undetectable. The air molecules resume their even distribution when the vibration ceases. Sound waves in air travel at a speed that is, to a good approximation, only dependent on the square root of the absolute temperature (i.e. temperature measured in kelvins, where 0 K is –273.15°C) giving a speed of 344 m s^{-1} at 20°C. The degree of power dispersed into the air from a sound source determines the volume or loudness of the sound.

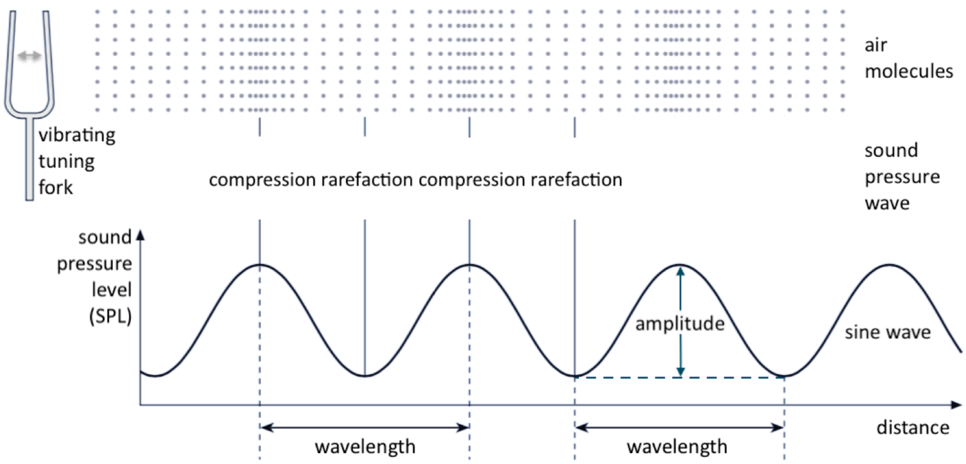


Figure 2.4 Representation of pure tone soundwaves in air and the resulting sine wave (after The Open University, 2009, p. 17, with permission)

The amplitude and frequency of these sound waves in the context of musical sounds are the subjects of the next two sub-sections.

2.3.3 Sound levels

Humans are capable of hearing a very wide range of sound levels, also referred to as sound amplitudes or just amplitudes (Figure 2.4), from the sound of a tuning fork to that of a full orchestra and chorus performing, for example, Beethoven's *An die Freude* at the conclusion of his Ninth Symphony. Rather than expressing sound wave amplitudes as absolute values they are expressed as a ratio, comparing the level of the sound heard at any moment to that of the accepted quietest sound humans can detect (known as the threshold of hearing). The unit for this ratio is the decibel (dB) where equal increments in decibel values correspond to equal multiplications of the ratio of two quantities. Decibels were created originally to express the ratios of powers. Consider two powers P_1 and P_2, the decibel value is given by Equation 2.1:

$$10\log_{10}\frac{P_1}{P_2} \qquad 2.1$$

However, the power of the pressure in sound waves is proportional to the square of their amplitude. The use of amplitude in sound measurement (Figure 2.5) is commonplace because simple measuring instruments can easily display this quantity. Such knowledge is important, e.g. when sounds are to be amplified or recorded, for peak values can cause unwarranted or unpleasant audio distortion.

If A_1 and A_2 are the amplitudes of the corresponding sound pressures P_1 and P_2 the decibel equivalent of the ratio of these is shown in Equation 2.2:

$$10\log_{10}\frac{P_1}{P_2} = 10\log_{10}\left(\frac{A_1}{A_2}\right)^2 = 20\log_{10}\frac{A_1}{A_2} \qquad 2.2$$

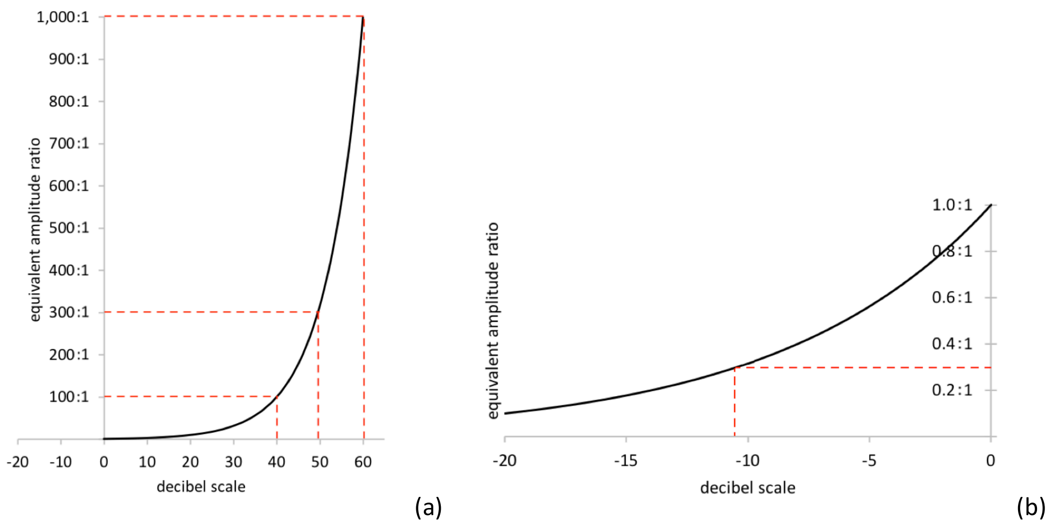


Figure 2.5 Relationship between amplitude ratios and the decibel scale (after The Open University, 2009, p. 41, with permission)

The relationship between the amplitude ratio and the decibel value is exponential in nature (Figure 2.5(a)). Thus, it can be seen that an amplitude ratio of 100 (i.e. a ratio of 100:1) is 40 dB. However, trebling the amplitude ratio to 300 does not lead to a decibel value of 120 dB (i.e. 3 x 40) but instead to an approximate value of 50 dB (actually 49.54 dB). An amplitude ratio of 1 (i.e. unity gain) is 0 dB and a value of –3 (i.e. ratio of 0.3:1) results in an approximate value of –10 dB (actually –10.45 dB), i.e. a negative gain or attenuation, as shown in Figure 2.5(b). Note the value of the ratio with negative gain can become very small but always remains positive, only the dB value becomes negative.

Sound amplitudes are usually measured in sound pressure levels (SPL), with units of decibels, and given by Equation 2.3:

$$SPL = 20\log_{10}\frac{pressure\ in\ pascals}{2{\times}10^{-5}} \qquad 2.3$$

where 2×10^{-5} pascals is the universally accepted level of the pressure amplitude at the threshold of hearing at a frequency of 1 kHz. A list of common sound pressure levels is given in Appendix 1. One example shows that orchestral music during loud passages can reach an SPL of over 110 dB.

2.3.4 Musical pitch

Musical notation

Western musical notation systems use letters of the alphabet from A to G to identify the seven musical notes that form an octave. This system is repeated in each octave. To identify each of the octaves that are used in musical notation a subscript number is applied to each note's pitch letter, 0 for the lowest octave to 7 at the highest. For example, "middle C", the note at the centre of a piano keyboard, is written as C_4.

Concert pitch

Haynes and Cooke (2001) describe frequencies as 'simply natural phenomena', that can only be assigned pitches when they are allied to a pitch standard. They state that:

> 'A pitch standard is a convention of uniform pitch that is understood, prescribed and generally used by musicians at a given time or place.'

Since the middle of the 20th century 'concert pitch' has become the international pitch standard where the note named A_4 (the A above middle C) is set at a frequency of 440 Hz ±0.5 Hz. For reference, the international standard tuning frequency ISO 16:1975 (ISO 2017) specifies:

> 'The frequency for the note A in the treble stave shall be 440 Hz. Tuning and retuning shall be effected by instruments producing it within an accuracy of 0.5 Hz.'

Musical notes

The fundamental frequency of a named musical note in any octave is double that of the similarly named note in the octave below or half that of the note in the octave above as shown in Figure 2.6.

With note A_4 set at concert pitch of 440 Hz, the frequency of A_3, an octave below, will be halved at 220 Hz, and A_5, an octave above will be doubled at 880 Hz, etc. The non-linearity of the note frequencies shown in Figure 2.3 makes it harder for humans to discriminate

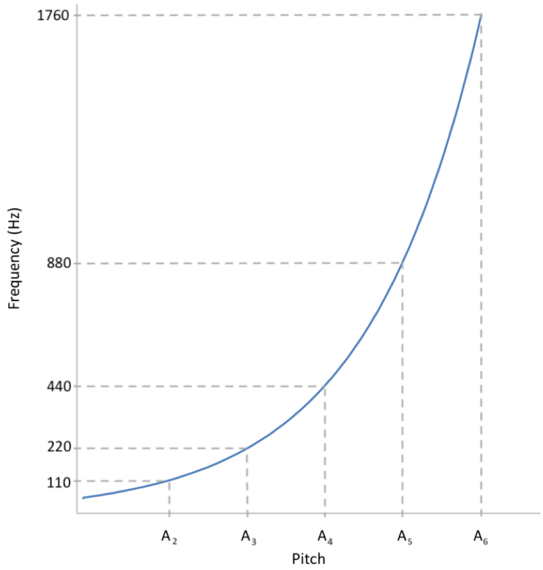


Figure 2.6 Non-linear relationship of frequency to musical notes (after The Open University, 2009, p. 36, with permission)

between lower pitched notes. This is because there are fewer cycles per second difference between lower pitches, with only 110 cycles per second between notes A_2 and A_3, whereas there are 880 cycles per second between notes A_5 and A_6. This is discussed in a sub-section below.

Although nothing was written down by Pythagoras in the 6th century BCE (Huffman, 2014), he is credited with discovering the rules of tuning, not by frequency but by using small integer ratios on the length of stretched strings of an instrument commonly termed the monochord (Figure 2.7).

Figure 2.7 Medieval illustration depicting the Roman philosopher Boëthius (~480–524 CE) playing a monochord

He discovered that when sounded together, string lengths comprising integer ratios, 2:1 (octaves) and 3:2 (perfect fifths), produced pleasing, agreeable sounds that are said to be consonant. The Pythagorean scale is any scale constructed from these perfect octaves and perfect fifths. Further experimentation with integer ratios led to five additional notes being interspersed between the seven standard notes, A – G, giving the 12 semitones of Western music systems. These additional notes were represented with the existing seven letters plus either a sharp (♯) or a flat (♭) sign as appropriate. The problem with using the Pythagorean scale of fifths is, when having ascended in steps of the ratio 3:2, i.e. in perfect fifths, through all 12 notes starting with the note C (i.e. C-G-D-A-E-B-F♯-C♯-G♯-D♯-A♯-E♯-C') which covers all seven octaves, the final note C' is slightly sharp by a ratio of 1.01364:1. This leads to an error known as the 'Pythagorean comma' (Howard and Angus, 2006, pp. 146-148). As Western music always requires the octaves to be the perfect ratio of 2:1, Pythagorean tuning is no longer acceptable. However, the problem was resolved through the development of several different musical temperaments, two of which are described in the following sub-section.

Temperaments and tuning

Modern musical instruments used in classical Western music are mostly tuned to 'equal temperament' where the notes within each octave are subdivided equally into 12 semitones, with each semitone further divided into 100 cents making 1200 cents in the octave. Given that the frequency ratio of the octave has to be 2:1, then the ratio of the frequencies of two notes of each equal tempered semitone will be the number, which when multiplied by itself twelve times, doubles the frequency. Mathematically, this gives the frequency ratio of the equal-tempered semitone as the twelfth root of 2 shown in Equation 2.4:

$$\text{Frequency ratio for an equal-tempered semitone} = \sqrt[12]{2} = 1 \cdot 0595 \qquad 2.4$$

Further subdividing each semitone into 100 equal divisions known as cents gives a frequency ratio for each equal-tempered cent as the 1200th root of 2, i.e. 100th of a twelfth root of 2 shown in Equation 2.5:

$$\text{Frequency ratio for an equal-tempered cent} = \sqrt[1200]{2} = 1 \cdot 000578 \qquad 2.5$$

However, the intervals between the notes are now not precisely harmonically related, unlike the intervals demonstrated originally by Pythagoras with his string lengths, and so are less consonant. In 'just intonation' the frequencies of the intervals are related to the fundamental or keynote by rational numbers so that the semitones of pure intervals are not equally spaced as demonstrated in Figure 2.8. The most pleasing intervals are those notes related by ratios of small integers. For example, taking the keynote as A_4 the perfect fifth, which spans seven semitones from A_4 to E_5 within the octave, has a frequency ratio of 3:2. Taking the frequency of A_4 as 440 Hz, E_{5just} is calculated to have a frequency of 660 Hz as demonstrated in Equation 2.6:

$$\text{Frequency of } E_{4just} \text{ as a perfect fifth} = f_{C4} \times \frac{3}{2} = 440 \times \frac{3}{2} = 660 \text{ Hz} \qquad 2.6$$

In equal temperament, the frequency of E_5 is 659.26 Hz as shown in Table 2.1. This makes the equal-tempered fifth from A_4 to E_5 very slightly flattened (by –2 cents) compared

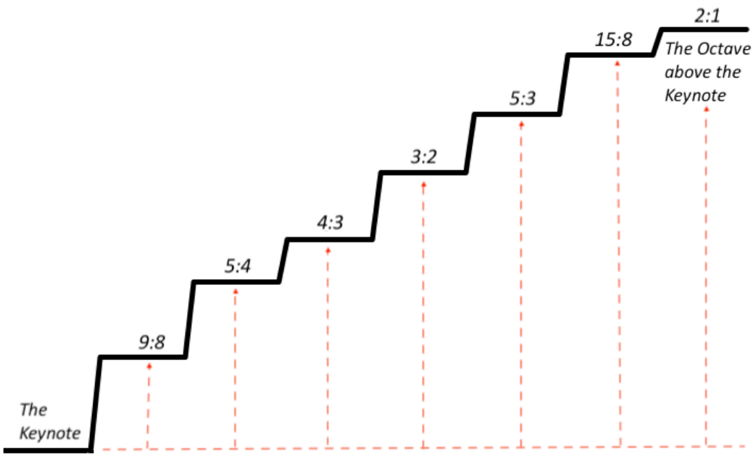


Figure 2.8 Just intonation showing the simple ratios of the eight notes of the octave demonstrating the uneven intervals (based on Powell, 2016, p. 160)

Table 2.1 Comparison of just intonation and equal temperament tuning for the A major scale from A_4

Note	Interval	Ratio	Just Intonation (Hz)	Equal Temperament (Hz)	Difference (Hz)	Difference (cents)
A_4	Unison	1:1	440.00	440.00	0	0
B_4	Major 2nd	9:8	495.00	493.88	–1.12	–4
$C\sharp_5$	Major 3rd	5:4	550.00	554.37	+4.37	+14
D_5	Perfect 4th	4:3	586.67	587.33	+0.66	+2
E_5	Perfect 5th	3:2	660.00	659.26	–0.74	–2
$F\sharp_5$	Major 6th	5:3	733.33	739.99	+6.66	+16
$G\sharp_5$	Major 7th	15:8	825.00	830.61	+5.61	+12
A_6	Octave	2:1	880.00	880.00	0	0

to the perfect fifth in just intonation. Overall, certain intervals in the equally tempered scale are dissonant to some ears due to the roughness in the sound caused by the slight difference in frequencies between the just and equal temperament tuning. However, equal temperament tuning is generally acceptable to most people as they have been brought up predominantly hearing this tuning system. The slightly irregular intervals are thus not perceived as being unpleasant.

The next section discusses the way in which humans recognise and process sound with particular emphasis on music.

2.3.5 Listening to music

Rasch and Plomp (1999, p. 89) describe musical tones as having three basic perceptual properties: pitch; loudness, and timbre. Further, they add that we perceive music as consisting of a blend of musical tones, beats and roughness, consonance and dissonance.

In regard to the basic property of pitch, the ear acts as a frequency analyser giving us the ability to discriminate such musical tones which are presented simultaneously within the complex sounds that we understand as music. A source, such as the singing voice described in the next section, generates a musical tone as a periodic sound pressure wave which is conveyed through the air to the ear, shown in Figure 2.9.

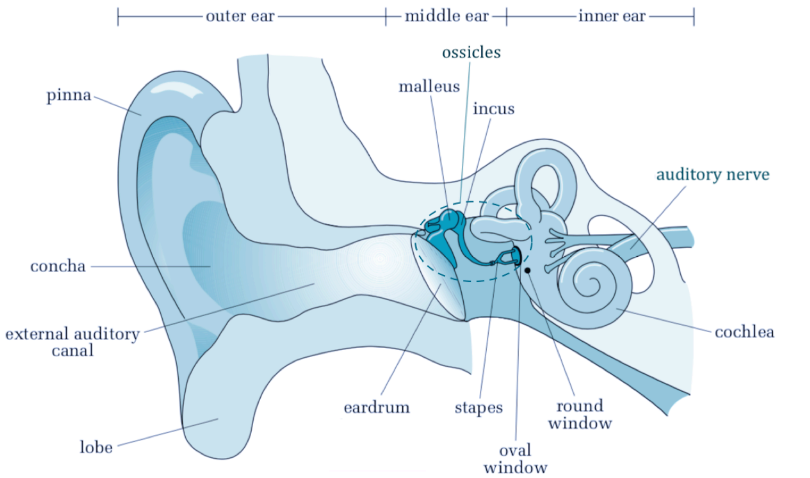


Figure 2.9 The Human Ear (after The Open University, 2009, p. 43, with permission)

The human ear consists of three sections, the outer, middle and inner ear. The pinna is the part of the outer ear which collects and directs sound waves through the external auditory canal to the eardrum, which will vibrate to and fro in sympathy with the received sound waves. The vibrations are transmitted via three small bones in the middle ear, collectively known as the ossicles, to the cochlea situated in the inner ear. The cochlea has a spiral structure approximately 2.5 cm long set in very hard bone. It acts as a transducer converting the sound vibrations to a series of electrical impulses. These signals are transmitted via the auditory nerve to the brain.

The cochlea, shown in an uncoiled form in Figure 2.10, has two ‘windows’ at its base; the oval window, which connects to the ear drum via the ossicles, and the round window which absorbs pressure changes in sympathy with the oval window. At the apex of the spiral a small hole called the helicotrema allows perilymph fluid to flow to the round window.

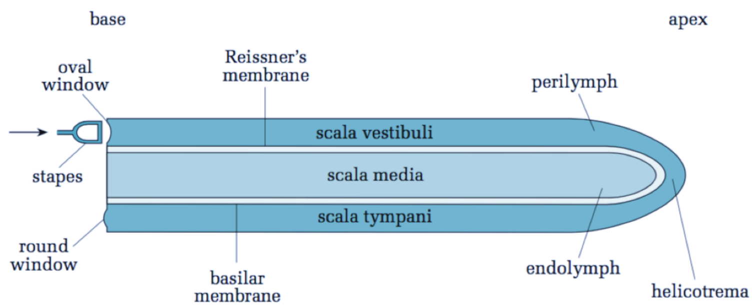


Figure 2.10 Cochlea uncoiled to show the internal detail (after The Open University, 2009, p. 46, with permission)

Vibrations in the oval window generate travelling waves in the perilymph which distorts the basilar membrane. Different groups of some 7,500 hair cells, situated in a single row along this membrane, shown in Figure 2.11, 'fire' electrical impulses into the auditory nerve when distorted. Beament (2005, p. 92) likens these pulses to 'Morse code' but comprised only of dashes – there being only one kind of impulse. These electrical pulse 'codes' are sent into the auditory nerve depending on the individual frequencies present in the sound wave. Once fired a hair cell takes just under a thousandth of a second (1 ms) to recover, making the recognition of frequencies above 1 kHz dependent on the order in which groups of hair cells fire. This is because the period of the sound wave above 1 kHz is shorter (< 1 ms) than the hair cell recovery time meaning the next cycle of the sound wave occurs before the hair cell has recovered. Below 1 kHz, where the period of the sound wave is longer (> 1 ms), one or more pulses may originate from a single hair cell as it has time to recover before the next

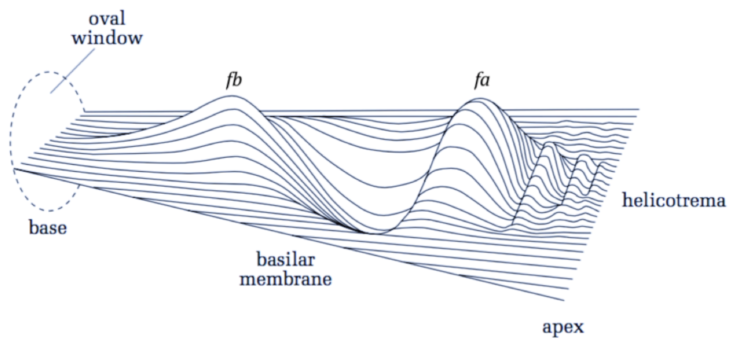


Figure 2.11 Distortion of the basilar membrane due to a pair of tones of different frequencies ($f_a << f_b$) (after The Open University, 2009, p. 48, with permission)

cycle occurs. Note that the hair cells nearest the oval window are sensitive to higher frequencies whereas those close to the helicotrema react to lower frequencies.

When two pure tones of frequency f_a and f_b are received simultaneously what is heard depends on the relationship between the two frequencies. If f_a exactly equals f_b then only one tone of a specific pitch is perceived. If the relationship between f_a and f_b is unequal but there is under 10 Hz difference between the frequencies, the sound will vary in loudness due to beating, i.e. an undulation of amplitude at a rate equal to the difference between the two tones, with a frequency which is an average of the two tones. For example, consider two tones f_a and f_b with frequencies of 440 Hz and 450 Hz respectively. When sounded simultaneously only a single tone with a frequency of 445 Hz will be heard, with variations in amplitude at the beat frequency of 10 Hz (i.e. $f_b - f_a$) causing the sound to appear to flutter. If f_b is increased to between 450 Hz and 500 Hz, the sound heard will be rough and there will be a beat frequency, heard possibly indistinctly, depending upon the separation frequency. If f_b is further increased to a frequency greater than above 500 Hz but under 530 Hz, the sound will still be slightly rough, but less dissonant, and two distinct pitches will be heard. At the point where f_a and f_b are around 100 Hz apart, two separate notes will be heard. The point at which the tones change from sounding rough to smooth is known as the critical bandwidth and is dependent of the initial value of f_a. A range of 24 critical frequencies, later termed the 'Bark scale', was proposed by Zwicker (1961, p. 248). Figure 2.12 shows the critical bandwidth of the ear as a function of the frequency (f) based on the centre frequencies of each critical bandwidth. With f_a below 500 Hz, the response is linear with a bandwidth of ~100 Hz. When f_a is above 500 Hz it increases logarithmically at a rate of $0.2f_a$.

Table 2.2 shows the fundamental frequencies covering the range of musical notes from B_1 to D_6. For notes below B_4 (f_c = ~500 Hz) the critical bandwidth becomes between two and eight semitones which makes discrimination between adjacent notes difficult.

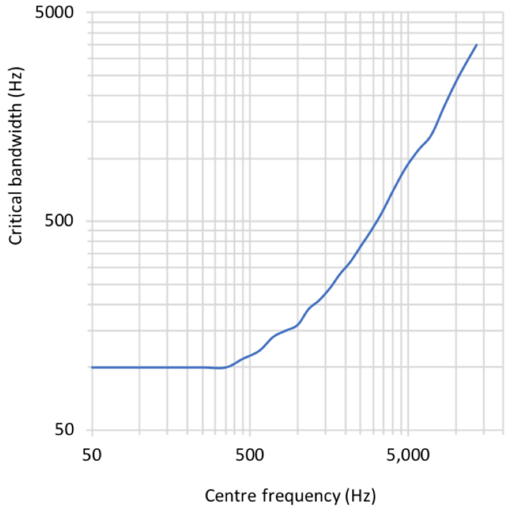


Figure 2.12 Critical bandwidth as a function of frequency (f_c)

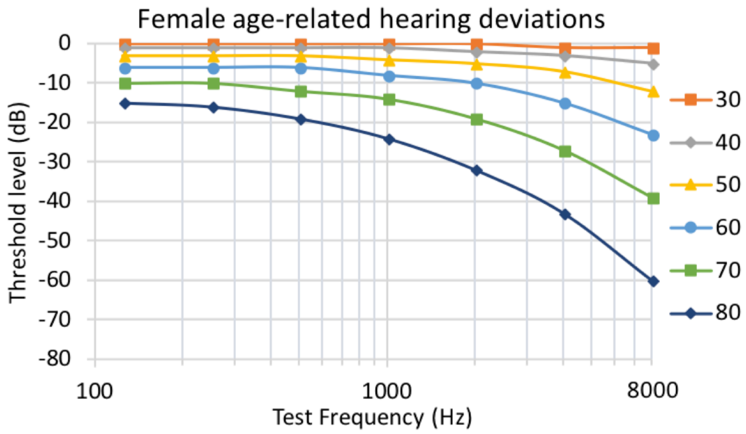
Table 2.2 Variation of critical bandwidth with musical tones within the voice range of singers (adapted from Zwicker, 1999, p. 159)

Centre frequency, f_c (Hz)	Note nearest to f_c (scale)	Frequency of the note nearest f_c (Hz)	Critical bandwidth centred at f_c		
			Hz	Cents	Semitones
50	B_1	61.7	100	767	8
150	D_3	146.8	100	516	5
250	B_3	246.9	100	319	3
350	F_4	349.2	100	232	2
450	A_4	440.0	110	205	2
570	D_5	587.3	120	168	2
700	F_5	698.5	140	143	1
840	$A\flat_5$	830.6	150	149	1
1000	B_5	987.7	160	135	1
1170	D_6	1174.7	190	135	1

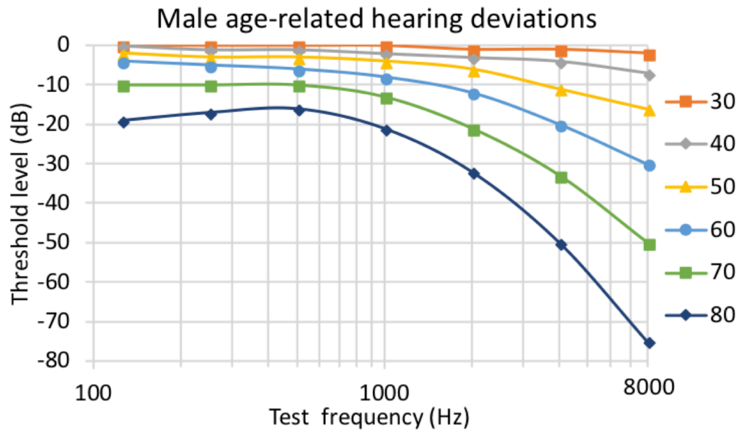
Above ~500 Hz the separation is closer to a semitone, so improving the ability of the ear to discriminate between adjacent pitches.

Young people with normal hearing are able to hear a range of sound frequencies from 20 to 20,000 Hz. The ability to hear high frequencies reduces gradually with increasing age due in part to damage occurring to the hair cells in the cochlea. This is due to the hair cells sensitive to high frequencies being situated closest to the oval window so bearing the brunt of loud sounds and thereby being more likely to be damaged over time, refer to Figure 2.10.

The gender differences in age-related hearing loss shown in chart (a) for females and chart (b) for males of Figure 2.13.



(a)



(b)

Figure 2.13 Median values of expected hearing threshold deviations at various ages of females (a) and males (b). Adapted from BS ISO 7029:2017, Appendix D. Permission to reproduce extracts from British Standards is granted by BSI Standards Limited (BSI). No other use of this material is permitted. British Standards can be obtained in PDF or hard copy formats from the BSI online shop: www.bsigroup.com/Shop

The difference between the two charts cannot be satisfactorily explained. However, it is well-established that long-term exposure to noise can affect the rate of hearing loss which, due in the past to differing work patterns, is the reason usually given as to why males suffering greater hearing loss than females. Kim et al. (2010) tested Korean subjects with little evidence of noise-induced hearing loss and found the expected differences although their tests showed less overall hearing loss in males than shown in Figure 2.10. They discovered a significant difference for the worse in senior males at 4 and 8 kHz. They were unable to provide any underlying biological causes for sex-differences in age-related hearing loss but postulated that hormone differences between men and women might bear investigation.

For all singers over 50 years of age normal hearing is flat up to 500 Hz but drops in sensitivity as the frequency rises from that point as compared with the 20–30-year group. However, this average hearing loss in older people may affect their ability to hear themselves and the other singers (an important factor in choral singing which will be discussed in later chapters). The top soprano note (C_6) has a fundamental frequency of 1046.5 Hz which will on average be perceived as 20 dB quieter and so are likely to be masked by other sounds. Another effect of aging is a narrowing of dynamic range, i.e. a narrowing of the range between barely perceptible and uncomfortably loud sounds. Herold (1987, pp. 24-25) sees this as a decided disadvantage to both singers and audiences for if loud sounds are tolerable then soft sounds are likely to be unheard.

Following this introduction to the human hearing system and the problems in decoding the musical sounds into useful information, the next section discusses the source of human musical notes, namely the singing voice.

2.3.6 Voice control

The human voice is a musical instrument with similarities to all other acoustic devices designed to make music when controlled correctly. The sound is generated by the vocal organ, which consists of the respiratory system, the vocal folds and the vocal tract. The action of the voice is shown in Figure 2.14.

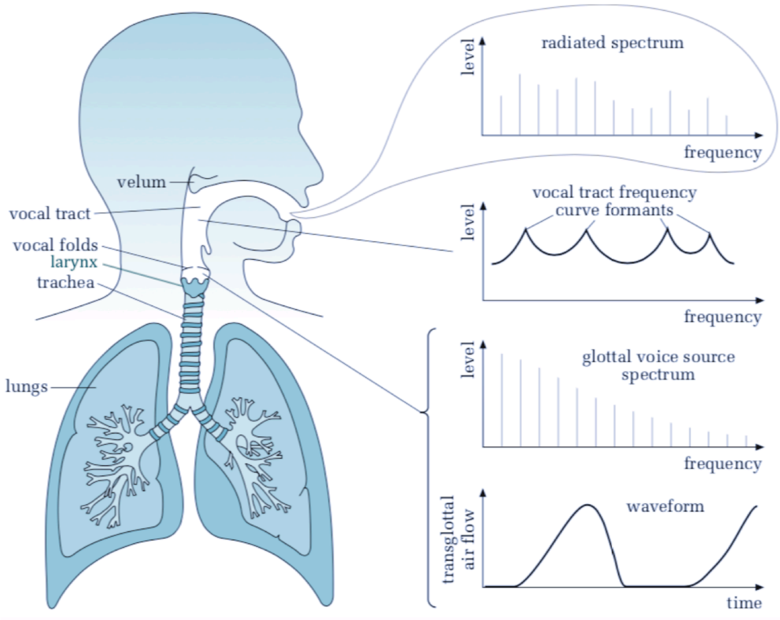


Figure 2.14 Illustration of the human voice system (After The Open University, 2009, p. 99, with permission)

To initiate a sound, compressed air is expelled from the lungs, usually at a pressure higher than for normal exhalation. This airflow is interrupted by the vocal folds rapidly opening and closing, generating periodically fluctuating differences in air pressure, and thereby creating a pitched sound. Muscles in the larynx stretch or relax the vocal folds to fine tune the rate they open and close, and hence modify the pitch of the sound produced.

Singing generally requires pitches that are higher than those used in speech. According to Sundberg (1999, p. 174) the average speech frequencies of males and females are 110 Hz and 200 Hz respectively. Table 2.3 lists the highest frequencies expected of the basic four vocal parts of any multipart choir: soprano; alto; tenor and bass (SATB).

Table 2.3 Highest frequencies expected from professional singers (after Sundberg, 1999)

Voice part	Frequency (Hz)	Highest note
Soprano	1400	C_6
Alto	700	F_5
Tenor	523	C_5
Bass	350	F_4

Note: these frequencies are somewhat higher that would be expected from amateur singers.

The sound produced by the vocal folds is often referred to as the 'voice source'. This is a complex sound consisting of a fundamental frequency (f_0) plus a number of harmonics (f_1, f_2 … f_n). At medium vocal loudness, the amplitude of these harmonics reduces at the rate of 12 dB per octave as shown in the glottal voice source diagram in the lower side panel of Figure 2.14, (Sundberg, 1987, p. 11). The number of vibrations of the vocal folds in one second is identical to f_0 and determines the pitch heard. The harmonics of the voice are referred to as *partials* and are numbered such that f_0 is termed the first partial, f_1 the second partial, etc.

The shape and size of the vocal tract causes it to act as a resonator. When the voice source generates certain frequencies internal reflections (produced in the vocal tract) can be in-phase producing standing waves. At these frequencies, known as *formant frequencies*, the amplitude of the sound is amplified. Frequencies that are out of phase do not resonate and become attenuated. Thus, the vocal tract formants appear as peaks in between areas of attenuated frequencies, as shown in the upper side panel of Figure 2.14. The sounds that come from the mouth are modified from that of the voice source by changing the shape of the vocal tract's *articulators* (i.e. lips, tongue, lower jaw, etc.). Note that these changes of shape mostly affect the two lowest formant frequencies which may be changed by two octaves or more. It is these two formants that largely govern the character of most vowels, that is the *vowel quality*. The higher frequency formants cannot be altered as much and so do not affect vowel quality but do contribute to the individual's *voice quality*. Unlike fretted or keyboard instruments, where the pitch of each note is fixed in relation to all other notes once the instrument is tuned, the voice can, within its range, produce any note across a pitch continuum. Choral singers are able to achieve both very fine control of the pitch by making small adjustments to their vocal folds and also a wide range of different pitches. Average human singing voices are able to span around two octaves, Figure 2.15 shows the typical pitch ranges for the singing voice classifications of professional singers from bass to soprano, related to the notes on a keyboard instrument.

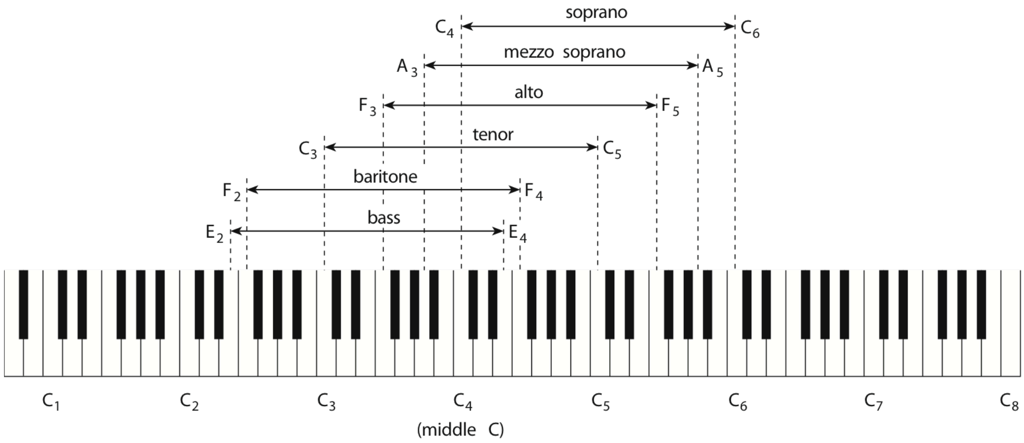
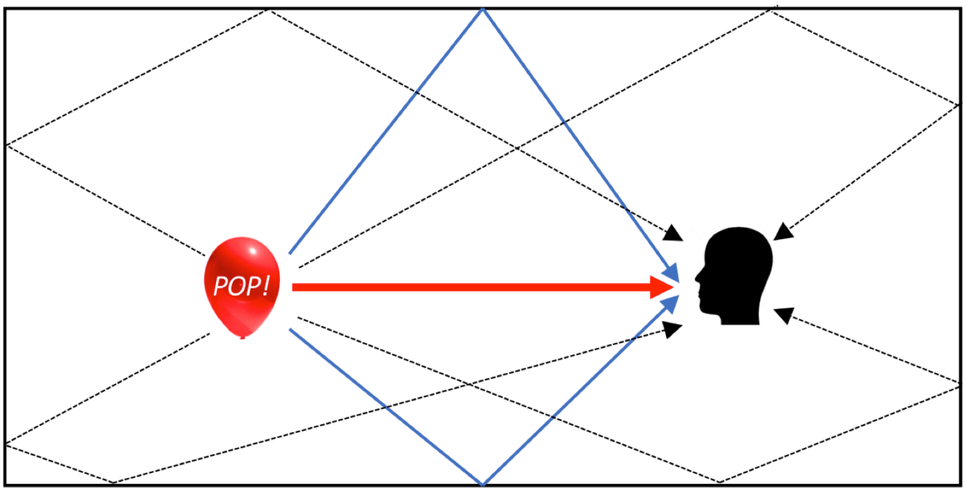


Figure 2.15 Diagrammatic representation of the pitch ranges of the main singing voice classifications for professional singers, (The Open University, 2009, p. 130, with permission).

2.3.7 Acoustics of venues

The venues in which choirs rehearse vary from rooms in private houses to the large spaces found in cathedrals. Wherever choirs perform, the space needs to be of a sufficient size to accommodate comfortably all the people involved. Choirs often rehearse in a smaller space than they use for public performances because of economic constraints such as hire costs, heating, lighting and there being no requirement to have additional space for an audience. No matter the size, all these venues have acoustic properties that may influence the performance. Traditionally, the acoustic properties of venues are categorised by the reverberation time (RT_{60}); that is, the time over which the sound energy introduced into the space decays by 60 dB, marked as reverberations in Figure 2.16. If RT_{60} is short, the space is said to be 'dead' (dry), whereas if it lasts for several seconds, it is described as 'live' (wet) (Howard and Angus, 2006, p. 281). To test the acoustic properties of a venue, the sound energy used to measure the reverberation time should cover the full range of audio frequencies from 20 – 20, 000 Hz. A high amplitude impulse sound, such as that from bursting a balloon or from firing a starting pistol, or a swept sine wave (chirp) from a



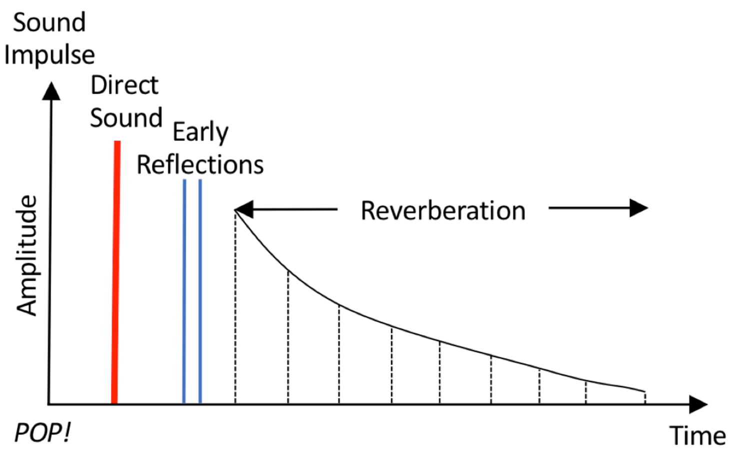


Figure 2.16 Representation of the behavioural characteristics of an impulse sound in an enclosed space, (after Howard and Angus, 2006, p. 269, with permission)

loudspeaker, which can be deconvolved into an impulse, are commonly used for this purpose. An impulse contains all frequencies so the behaviour of the room can be measured. The total sound energy in the venue, initially generated by a stimulus, may be regarded as having three distinct behavioural characteristics, shown in Figure 2.16.

The resulting sound may be evaluated using either computer software or dedicated measuring instruments:

- *Direct sound* – after a very short time delay (e.g. < 10 ms) the impulse sound will be heard. It will have travelled directly to the listener and therefore the shortest distance.

- *Early reflections* – after a slightly longer delay (e.g. 20 – 100 ms) sounds reflected once off walls, ceilings, etc. will be heard coming from different directions to that of the direct sound.

- *Reverberations* – at an even later time (> 100 ms) sounds coming from all directions following multiple reflections will be heard. They decay exponentially (i.e. not constant with time), as shown in Figure 2.16.

Howard and Moretti (2009) describe the following three measurements as the most important indicators in defining a performance space:

1. *Early Decay Time* (EDT) – six times the time in seconds for the sound energy to decay by 10 dB from its maximum. In a concert hall an EDT of less than two seconds is desirable for clarity of complex *a cappella* music.

2. T_{30} – the time in seconds for the sound to decay by 30 dB which is extrapolated to produce the standard RT_{60} measurement.

3. *Clarity index* (C_{80}) the ratio of the early sound energy in the first 80 ms of the measured sound relative to the reverberant sound energy remaining after 80 ms, both measured in dB. For listening to singing, a clarity index of 0 dB is good and a range between +1 to –4 dB is acceptable. This lets the audience appreciate fast tempos and makes the words clearer, both of which may be blurred by the higher sound energies from longer reverberation times.

These indicators are important considerations for the pleasure of audiences, but what of the effects of these acoustic characteristics on singers? Ternström and Sundberg (1986, pp. 59-69) express concerns that a choir singing with a given effort will sound louder in a reverberant space making it more difficult for individual singers to hear their own voice, an important consideration in maintaining pitch and discussed in later chapters. They further state these problems may be compounded by positioning the singers too close to one another. A spacing of a metre between singers is recommended (although seldom if ever followed) in a venue with a two second reverberation time, such as is often found in concert halls and places of worship, to ensure singers can hear themselves against the rest of the choir. For venues with shorter reverberation times this spacing could be reduced whilst ensuring sufficient space for the singers to be comfortable.

2.4 Summary

This chapter has covered the theory which underpins the research practices which will be described in the remainder of this thesis. Musical sounds are complex waves which are conveyed to our ears by vibrating air molecules in the atmosphere. The unit of sound level (amplitude) is the decibel, the ratio of the actual level heard to that of the threshold of hearing. Musical pitch is a property of a sound which has associated to it a specific name and octave designation and fundamental frequency. Concert pitch is an international standard whereby the fundamental frequency of note A_4 is set to 440 Hz ±0.5 Hz. The fundamental frequencies of all other notes in the musical scale are defined by this standard. The octave represents a doubling or halving in the fundamental frequency of each similarly named note in the scale but the difference in frequencies between notes within the octave are dependent on the temperament employed. The hearing mechanism of the human ear is discussed in relation to the musical scale which is important in discriminating between notes. The effects of aging on our ability to hear the range of musical notes are demonstrated. The production of sounds by the human voice followed along with an opportunity to consider the singing voice classification which will be found in most amateur choirs. This chapter concludes with a discussion of the acoustic properties of the venues used by choirs to rehearse and perform. The three specific sounds, direct, early reflection and reverberations which occur in closed spaces are described and the resultant parameters used within this research introduced.

The next chapter reviews the academic literature on pitch drift, commencing with examples of where pitch drift has occurred when singing unaccompanied music. Having identified pitch drift as a problem, the literature review reveals possible causes which may lead to the occurrence of pitch drift, including: the importance of listening, possible effects of tempos, choir layouts, and the environmental factors within the performance venue. Research into how the brain identifies and places musical pitches is discussed, along with an aside on the merits or otherwise of having 'absolute pitch'. The chapter concludes with a review of past and current research into tuning, ending with a very recent paper which introduces new thinking on why singers are unable to pitch their voices as accurately as violinists are able to pitch their violins.

Chapter 3
Literature review

> 'The ear usually hears what it wants to hear, even if that does not correspond to the acoustically given interval – which is indeed to great purpose, since with absolutely pure intonation, which never occurs in practice, the enjoyment of music would be impossible.' (Leonhard Euler, 1764, cited in Winckel (1967) p. 128)

3.1 Introduction

Pitch drift whilst singing *a cappella* music is a phenomenon that has been discussed for centuries. The opening quotation from Euler suggests that he did not expect singers to stay in tune, for if they did the overall sound would be all the poorer! The first part of this statement is entirely in accord with this research, whilst the final section appears to say that if performances were to adhere strictly to pure intonation some very unpleasant sounds would occasionally result. Though, with no reliable means of either comparing or recording performances for subsequent analysis, interest in studying intonation and pitch drift in *a cappella* choirs waned. It was not until later in the 19th century that developments in audio recording machines (Edison, 1877), cited by Miller (1916), allowed sung musical pitch to be analysed by quantitative methods. Miller initially used a phonograph to investigate the properties of sung vowels by varying the rotational speed of the record. He went on to develop the 'Phonodiek' for analysing pitch, which was capable of working up to 10 kHz and projected a live waveform onto a screen suitable for use in a lecture. Seashore (1938) developed ways of investigating various aspect of singing performance including vibrato and intonation with his tonoscope, a device for measuring pitch, which is discussed further in a more complete treatment of the history of pitch measurement in Section 6.3.

A resurgence of interest in early music (i.e. music of the medieval, Renaissance, and early baroque periods) in the mid-20th century (Devaney and Ellis, 2008) stimulated research into earlier tuning systems as instrumental ensembles and choirs strove to perform ever more historically accurate performances. Latterly, work undertaken by Sundberg (1987); Ternström and Sundberg (1988); Ternström (2002); Jers and Ternström (2004) based at the 'Speech, Music, and Hearing' group at the Royal Institute of Technology in Stockholm, generated renewed interest in variations in pitch drift. The work of Vurma and Ross (2006), and Howard (2007, 2013 and 2015) promoted increased interest in the subject. However, their research involved either soloists, quartets or small ensembles of specially selected singers, and was usually based in laboratories with the singers equipped with either video laryngoscopes (an instrument for viewing the vocal folds) and/or individual microphones feeding multi-channel recording machines. This would allow consistency of such variables such as the selection and attendance of the singers and environmental factors, something not necessarily possible when undertaking research with amateur or professional choirs. This may well be why there is little evidence of research with choirs. Lottermoser and Meyer (1960) measured the intonation of three professional choirs from gramophone recordings. Devaney et al. (2012) employed statistical machine learning techniques with MIDI score files auto-aligned to audio recordings to automatically extract performance information including note timings, intonation, vibrato rates and dynamics.

It is the recent ability to analyse quantitively the pitches of the individual voice parts within choirs from a series of audio recordings of choral performances that made investigations into why pitch drifts irregularly from rehearsal to rehearsal possible (Section 6.4).

3.2 Examples of pitch drift

3.2.1 Singing in New College, Oxford

In a radio programme (*Key matters – B minor,* 2012), Simon Halsey, the chorus director at the time of both the City of Birmingham Symphony Chorus and the London Symphony Chorus, recalled:

> 'I was a choir boy in New College, Oxford, and for two years we had no organ as it was being rebuilt so sang every single day *a cappella*, and very often, on a Friday when it was snowy outside, and everyone was tired, we used to have intonation problems and the piece would begin in E flat and end down a semitone. I remember Sir David Lumsden getting rather cross about this and deciding he would try initially to sing all the pieces in E, a semitone higher than they looked, and interestingly the intonation stayed. Now the question was why did it stay, and I still can't tell you? But I think because it felt brighter, because we'd been told it was higher and because it required a great deal more connection of our diaphragm, our lungs to our vocal chords, because it was higher and a bit more effort we probably worked harder brightened the sound and the pitch stayed.'

Evidence here then that even a first league choir struggles with pitch drift from time to time. Also, Halsey gives us his thoughts into what are the possible causes of pitch drift, with mention of internal factors such as key changes alongside external factors with his allusions to the end of the week and wintry conditions. However, an admission by such a well-respected chorus director that he does not know what causes problems with pitch demonstrates that research in this area is timely and the findings should prove useful to the choral community. He also states that the pitch goes flat rather than sharp, a phenomenon well-known to choral singers and their leaders.

3.2.2 Additional suggestions

Potter (2000) states that pitch can be affected by all sorts of extraneous reasons including, as examples, the weather, central heating and humidity. He does go on to say that performers should not overly worry about pitch as the overall performance may be more acceptable and the audience more settled by staying in the pitch to which the performers have slipped. This not only introduces additional evidence, albeit anecdotal, of physical conditions affecting pitch but that again, as with the previous example, the pitch has gone down. Potter also confirms that finding a more suitable initial pitch may lead to a more stable performance, supporting Halsey's statement.

3.2.3 An example: performing Bruckner's *Os Justi*

The problems of pitch drift encountered by a university choir when singing Bruckner's *Os Justi* are described by Terasawa (2004). He posits that this particular work is seen as the cause for the choir losing a semitone each time it is sung. He reports that usually the choir's musical director was able to work out which part of the music had caused the pitch drift, e.g. a change from a diatonic to a chromatic scale or a particular leading note, but this was not the case when singing this particular piece. He supposes that pitch drift is dependent on many factors in a musical performance, such as the skill of the performers, the difficulty of the piece or psychological stresses. He also lists possible reasons for pitch drift including: the acoustic environment, the time of day, the singers present in the choir, and the composition of the repertoire. However, at the heart of this paper is the premise that the composition of the music is the primary cause of the pitch drift. Teresawa undertook a further series of psychoacoustic experiments with five singers from the Centre for Computer Research in Music and Acoustics at Stanford University, USA. His experiments compared chord sequences using both just intonation and equal temperament and indicated that the particular sequence of root notes for the chords in *Os Justi* may be the cause of the problem of pitch drift. His conclusion states that should the root notes (referred to by Terasawa as the 'fundamental bass' but is now termed the 'root note') of a piece be composed of complementary ascending and descending intervals, the music would be:

> '…more robust from the pitch drift point of view.'

which, Terasawa demonstrated, is not the case for *Os Justi*.

Here then is a suggestion that the composition of an *a cappella* work may cause the pitch to drift. This will be of importance when considering the music to be sung by choirs supporting this research, but only to the extent that the pitch should drift in the same manner each time the song is performed for, as Teresawa states in his introduction, *OS Justi* always ended exactly a semitone flat whenever it was sung.

3.3 Causes of pitch drift

In the introduction to this chapter, reference was made to a prevalence of interest into pitch drift. Internal factors to the music such as starting keys or pitch and chord succession, discussed by Terasawa, have been suggested as causes of pitch drift along with external factors such as physical condition of the performers, such as fatigue, mentioned by Halsey. The following sub-section introduces appropriate literature which discusses various factors which may influence the abilities of choral singers to maintain pitch.

3.3.1 Listening to oneself and others

Ternström and Sundberg (1988) discovered that the accuracy of the fundamental frequency (f_0) of a choral singer deteriorated abruptly when what they termed the 'reference sound', that comes from the rest of the choir, was too loud. This may seem surprising as it is generally thought useful to be able to hear the other parts. However, they found that an imprecision of pitch was due to the sudden masking of the feedback of the performer's own voice, making any comparison with the other singers difficult.

The importance of auditory feedback for singers is stressed by Tonkinson (1990) who researched the 'Lombard Effect', whereby an individual subconsciously raises their voice level as the background noise increases. He found this effect happens in choral singing in just the same way as it would in any noisy environment. Good singing practice should mean that choral singers do not raise their voices above reasonable limits to ensure their vocal folds are not strained (Howard, 2015, p. 78). Often, this is not the case and, given the above evidence, may be a contributing factor to pitch drift.

Working with individual singers, Mauch et al. (2014) reported that pitch drift was common in solo singing but only to a small extent (less than 20 cents over 50 notes) and not correlated to pitch accuracy, interval accuracy, or musical background. They found that masking caused by background noise did not appear to make pitch drift any more significant than with the noise removed, which rather contradicts Tonkinson's findings. However, the introduced noise is described in the paper simply as 'pink noise at a moderate sound pressure level', with no indication of actual levels given. Tonkinson used levels up to 95 dB SPL which accords with Ternström and Sundberg (1983) who found SPLs of between 80 and 100 dB to be normal in a choir.

Howard and Angus (2006) describe how, when singers have finely developed listening skills, they are able to make subtle changes in pitch by adjusting vowel colour and loudness, with the singer knowing automatically how to shape the vocal tract for a particular sound. Subsequently, Howard (2007) demonstrated that choral singers exhibit very fine control over the pitch through an ability of their vocal folds to make micro adjustments to f_0. Further, a second mechanism termed kinaesthetic feedback allows control of pitch when the reference sound is blocked and may be employed when singing in a strident choir. The knowledge singers have subconsciously learned about the positioning of their vocal folds, by feedback from nerve endings into the central nervous system, is then used for pitch control. Ward and Burns (1978) found that non-singers were less accurate than trained singers when auditory feedback was absent. Choral singers must be skilled at listening to those around them to ensure they each produce a blended sound which contributes to the most pleasing and consonant performance possible. Vurma (2010) describes how professional singers try to maintain pitch when paired together in unaccompanied performances. He found that, as individuals, professional singers preferred to maintain the pitch of their own part and ignored any deviations by their co-singers, relying on their inner standards and ignoring any mistuning of the accompanying voice. This may be seen as problematic depending on the singer's relative position within the body of the choir to both their own and other parts, assuming polyphonic music is being sung.

3.3.2 Effects of the tempo at which the music is sung

Jers and Ternström (2004) recorded an SATB ensemble of 16 singers, with four singers to a part. Each singer had a microphone connected to one track of a 16-channel recorder. They sang in unison (with an octave between the high (SA) and low (TB) parts) the 8-bar canon of Michael Praetorius's *Laudate Dominum* (Figure 3.1), employing both normal and slow tempos.

Figure 3.1 Eight bars of the canon *Laudate Dominum* by Michael Praetorius (notated for the tenor voice)

Analysis of the intonation of all 16 singers, singing in unison, showed that the pitch was more accurately maintained at a slow tempo (crochet = 80 bpm) than at the normal tempo (crochet = 125 bpm). Interestingly, and in contrast to most cases cited so far, the pitch was found to drift in an upwards direction over the eight bars by an average of +39 cents at the slow tempo. This was on the larger intervals (fifths and octaves). The pitch rose by an average of +55 cents at the normal (faster) tempo, implying that if there is less time to produce the note then inaccuracies and instabilities will increase. They suggest that synchronisation of singers, i.e. ensuring they all keep together, may play an important part in pitch control, agreeing with Mürbe et al. (2002) who had also established from experiments with soloists that errors in pitch increased when they sang fast staccato notes rather than slow legato ones.

3.3.3 Acoustic properties of the room

A survey of 32 musicians (musical directors, instrumentalists and singers) regarding their requirements of room acoustic characteristics was undertaken by Gade (1986). The responses are detailed in Table 3.1. They show the specific parameters of particular concern to soloists and ensemble musicians to be different. The soloists were concerned about the acoustic properties of the room whereas the ensemble musicians were interested in audible and temporal communication between each other.

Table 3.1 Subjective room acoustic parameters of relevance to solo and ensemble musicians (after Gade, (1981))

Solo musicians	Ensemble musicians
Reverberance	Hearing each other
Acoustic support	Time delay
Timbre	-
Dynamics	-

Pertinent to this research are the responses of the ensemble musicians, as both 'hearing each other' and 'time delay' which was emphasised by Ternström and Sundberg. Individuals within the ensemble must be able to hear each other, but not to the extent that their own sounds are masked. Further, the members of any ensemble must not be so far apart as to cause rhythm and tempo to be affected. This is especially important with choirs as it has been shown that fast tempos may cause pitch drift.

3.3.4 The layout of the choir

The layout of choirs (depending on the number of singers, the dimensions of the venue, and in particular the staging if at a performance) can lead to a time delay across the parts.

Ternström et al. (2012) list the advantages and disadvantages of commonly used layouts of four-part (SATB) choirs. They report that singers in typical block and row formations, shown on the left and middle of Figure 3.2, may become far-separated from each other. This presents particular difficulties to those on the edge in hearing other parts, whilst those situated in the middle of the choir found problems with hearing their own voice against the others. Mixed layouts, shown on the right of Figure 3.2, tend to need more experienced singers who won't mind being separated from others on their part. Anecdotal evidence suggests musical directors prefer the sound produced by their choirs when they experiment with this layout.

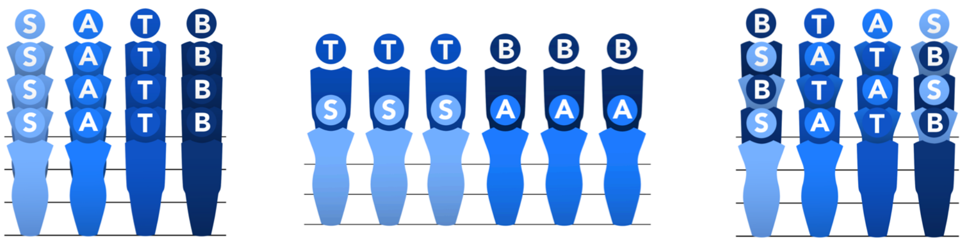


Figure 3.2 Common configurations employed by SATB choirs (after Ternström et al. (2012)). Diagram by Golton (2018)

Ternström stresses the importance of singers hearing their own voice against the sound from the choir which will include both direct sounds and sounds reflected from the walls, floor and ceiling of the room. Direct sounds tend to project forward into the room until they are reflected off hard surfaces. Singers will hear direct sounds from those individuals behind them, and to a lesser extent at the side, as well as reflected sounds somewhat later in time. This may or may not be of an advantage depending on the layout of the parts in the choir. As suggested above, the later arrival of reflected sounds may cause problems with pitch depending on the room acoustics and the works being performed. Those singers at the back will hear themselves but little else apart from reflected sounds. Ternström suggests the use of the score as a personal reflector if singers cannot hear themselves and acoustic reflectors around the whole choir when singers cannot hear each other. This is supported by Howard

(2015) who acknowledges the difficulty of hearing oneself against the other singers and also suggests the use of the score as a sound reflector.

On the whole, choral singers prefer to perform in a fairly reverberant acoustic to blend the sound, reducing the impact of direct sound (i.e. hearing an ensemble sound rather than individual singers) and improving the ability of the singers to hear each other.

Stephens and Bate (1950) developed a formula for demonstrating the optimum reverberation time for different applications: speech, orchestras and choirs. The plots for different sized enclosed spaces are shown in Figure 3.3. The formula assumes a frequency of 500 Hz. Choirs are shown to require the most resonant spaces in which to perform, which agrees with preferences of singers and music directors.

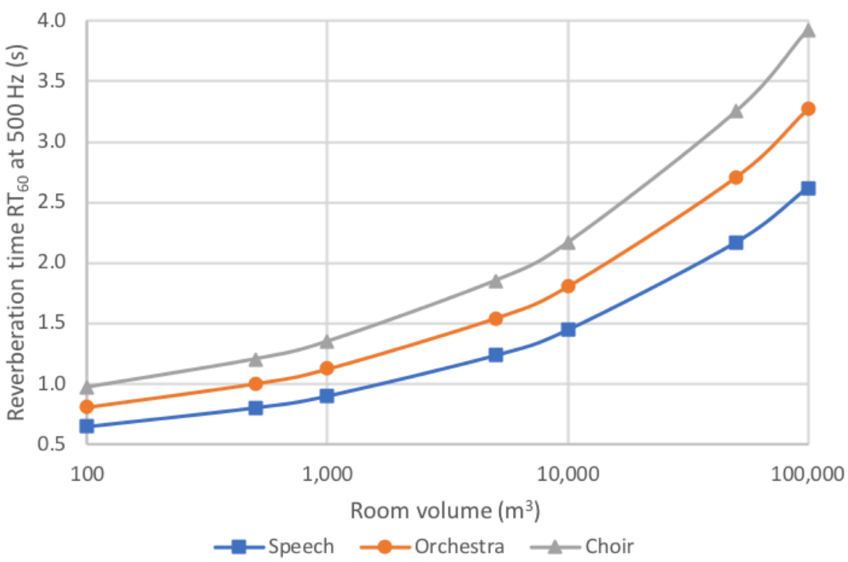


Figure 3.3 Stephens and Bate chart showing the ideal reverberation times in seconds for different applications in enclosed spaces ranging in size from 100 to 100,000 m^3

Howard and Moretti (2009) describe how the complex polyphonic music of the 16th century sung in the great churches of Venice needed very particular acoustic characteristics in terms of resonance to ensure clarity of performance. These characteristics could be realised by placing heavy tapestries on the walls around the chancel and/or changing the position of the singers. This may well have been a way of ensuring singers could hear themselves and each other. They also stress how the acoustics would have been improved by the presence of the multitude of clergy, dignitaries and worshippers who would have attended the many religious and ceremonial services.

3.3.5 Environmental factors

Temperature and humidity can cause many instruments to vary in tuning. Ellis (1880), cited in Haynes (2002), wrote that:

> 'In point of fact, the exact pitch of an organ cannot be ascertained, for it is so large that various parts of it are constantly at variable temperatures and hence constantly liable to be at different pitches, or out of tune with each other.'

Tuning woodwinds and stringed instruments before a concert is essential. Often, retuning is required, especially with 'early' instruments which use more traditional materials that are sensitive to changes in temperature and humidity. But what of the human voice? No experimental results could be found regarding temperature and humidity causing pitch drift. There are anecdotal accounts such as that of Halsey, at the beginning of this chapter, who implies, amongst other things, that a snowy evening could cause tuning problems. Potter also refers to the weather, central heating and humidity being potential causes of pitch drift but without substantiation. Again, in his book, Howard (2015) makes reference to low humidity drying the airways and low temperatures affecting muscle action, which in both cases could cause damage to the tissues of the body rather than pitching problems. Naturally in a suitably controlled environment, singers will be happy and relaxed, or at the very least have one thing less about which to complain!

3.4 Pitch recognition

The extent to which pitch drift matters is difficult to assess for it depends on the ability of both performers and audience to hear if pitch drift has occurred and, if so, whether they are concerned.

3.4.1 Determining pitch discrimination

According to Seashore (1938) the average unselected group of adults were capable of recognising a change of approximately 3 Hz at the then (1930s) international pitch of A_4 of 435 Hz. This represents an ability to detect a change of pitch of ±12 cents. Thus, any pitch drift occurring within these bounds should not be noticed by an average listener. Seashore cites Stucker (1908) who found that the discrimination of professional musicians at the Royal Opera in Vienna was such that the keenest of them could distinguish better than 1 cent and the weakest 4 cents, well above the average of the population in general. It was Seashore's belief that these exceptional responses were due to people with extremely 'fine ears', having received a high order of training.

Kishon-Rabin at al. (2001) compared abilities to discriminate non-musical frequencies (i.e. tones that are not set at the frequencies which represent notes in the musical scale) between professional instrumentalists (none were singers) and non-musicians, both groups being in a similar age group. Their tests used three groups of tones starting at 250, 1000 and 1500 Hz respectively. Each tone group consisted of a pair of reference tones and an offset tone which was one of twenty 0.5 Hz steps (giving a maximum offset of 10 Hz) for the 250 Hz group, and one of twenty 1 Hz steps (giving a maximum offset of 20 Hz) for the two other groups. Adaptive testing presented each subject with tone groups consisting of two reference tones and one offset tone commencing with the largest offset tone. The subjects were asked to identify the offset tone amongst the three tones presented. Tests were repeated, gradually reducing the offset until a wrong answer was received. The offset was then increased until the response was correct and then reduced again until a threshold discrimination was finally achieved. Each tone group was repeated three times. The results revealed that the professional musicians performed better than the non-musicians but there was an overlap between the two in that the best of the non-musicians were better than the poorest of the instrumentalists. These findings agreed with those of Watson and Spiegel (1984) who found that, of the non-musicians tested, half were in the same discriminatory range as the musicians. Most noticeable though was a realisation that the repetition of the tests improved their subjects' threshold levels in all cases. Further, by taking professional instrumentalists from both contemporary and classical genres for their tests, Kishon-Rabin found the latter performed better. Finally, both of the above research outcomes demonstrated their subjects' pitch discrimination improved with repeated testing, supporting the notion that training will improve pitch discrimination.

This view is reinforced by an unexpected result from new research by Dance and Shearer (2017) who, whilst testing the hearing acuity of music students on both entry and exit of a four-year period of music studies, noted an average improvement of approximately 9dB HL (decibels, Hearing Level). As their research used an automated screening audiometer generating five tones between 500 Hz and 8 kHz, which is essentially a listening test, an overall improvement in listening appears to have been gained from their training. It would be interesting to know whether this improvement is associated with the improvement in pitch discrimination which will have developed during their musical training.

3.4.2 Musical categorization

Listening is the first stage in the process of recognising a musical tone, the mechanics of which were explained in the preceding chapter. Psychoacoustics is the study of the perception of sound, with music psychology being one of its branches. It aims to explain the means by which music is recognised, produced and acted upon.

Locke and Kellar (1973) report on categorical perception within music, that is the ability of the brain to make sense of the musical notes forming a chord (e.g. a triad) even when there are inaccuracies in the original stimulus. They subjected both singers and non-singers to a series of comparisons between an equally tempered A major triad (based on A_4, 440 Hz) and the A minor triad where the major third was flattened in a random fashion in one of seven steps between C♯ and C. Three groups of tests were presented to each subject on ten occasions to ensure the results had statistical significance. The results of the musicians and non-musicians were different, the former showing an ability to identify a switch from a major triad to a minor triad at a similar step of the seven between the two note values. The non-musicians switched over a wider range of steps. However, with both groups the triad was always placed in one of two categories, it was never recognized as being out of tune, thus demonstrating that the brain wants to categorize the out-of-tune chord and place where it is likely to belong. This suggests that our hearing system is somewhat forgiving and not appearing as accurate as might be thought.

In demonstrating the brain's categorisation of musical sounds, Powell (2016) suggests that Locke and Kellar were careful to choose the major third rather than say the perfect fifth in the triad. Referring back to Section 2.3.4 in Chapter 2 the simple ratio of C♯ compared to the keynote A is 5:4. This will already be very slightly rough sounding to the ear as compared say to the perfect fifth (E) with a simpler ratio to the keynote of 3:2. Powell further states that, had they varied the perfect fifth in place of the major third, this would have been more noticeable. This suggests particular care should be taken in their tuning by those singing in the vocal parts responsible for the octave and the fifth, as any drift will be more obvious to listeners than will be the case for the vocal part singing the third. In the case of an equally tempered A major scale based on A_4 (440.0 Hz) the third is sharpened by 14 cents (4.37 Hz) and will exhibit roughness (due to beating) whereas the fifth is only flattened by 2 cents (0.74 Hz) making any beating difficult to perceive but any pitch drift more obvious.

Locke and Kellar's research was reinforced by Siegel and Siegel (1977) who asked six specially selected music students (instrumentalists) to identify a series of 13 intervals, ranging from 20 cents below a perfect fourth to 20 cents above a perfect fifth, and judge whether they were in or out of tune based on equal temperament tuning. This will be a total range of 240 cents with 20 cents between each interval. Collectively they identified 63% of the intervals to be in-tune (even when the interval was out by 20 cents) whereas in fact only 23% were tuned correctly. The report concluded:

> 'Musicians had a strong tendency to rate out-of-tune stimuli as in-tune. Their attempts to make fine judgements were highly inaccurate and unreliable.'
> (Siegel and Siegel 1977, p. 405)

Evidence here that pitch recognition is far from straightforward and being in tune and out of tune is not simply a matter of departing from a particular mathematical relationship but a matter of musical context.

Training can help with pitch discrimination as demonstrated by Watson and Spiegel. However, both Locke and Keller and Siegel and Siegel contend that a certain amount of drift, at least to 20 cents, is acceptable even to the well-trained ears of experienced musicians. Ternström (1993) reported that ten experienced choral practitioners considered a pitch deviation of ±14 cents to be *tolerable* [his italics]. This may seem at odds with Seashore's finding that on average we can detect a difference between two tones with a difference of ±12 cents. However, there are no categorizing effects taking place in pitch discrimination tests as the subjects had not had an opportunity for prior training. Micheyl et al. (2006) compared the pitch discrimination abilities of groups of classically-trained musicians and untrained subjects before and after psychoacoustical training. They found mean thresholds to be six times greater between the two groups before training. This reduced to four times after both groups undertook a two-hour training session. A further procedure found that between four and eight hours training was necessary to bring the untrained group to the same level of discrimination as the musicians. No subsequent tests were made to determine whether this training led to permanent improvements in pitch discrimination.

3.4.3 Absolute pitch abilities

There is a certain mystique surrounding those individuals who possess absolute pitch. Ward (1999) describes ‘absolute pitch’, also known colloquially as ‘perfect pitch’, as the ability to identify the frequency or pitch of a specific tone, or equally, to pitch a note or desired frequency without referring to a reference tone. Anyone requiring a named tone to pitch another note in the scale is said to possess ‘relative pitch’, a skill which may be learned with practice, but which still comes, as Seashore (1938) affirmed, more easily to some people than others. Révész (1913) and Bachen (1937), cited in Ward (1999), contended that absolute pitch is an innate ability whereas Abraham (1901) and Copp (1916), also cited in Ward, suggested it is developed in early childhood. On the other hand, Seashore stated absolute pitch to be very rare and was uncertain how it developed. There are reports of adults acquiring absolute pitch, following months of training, to a level of pitch naming equalling those possessing it from childhood. However, Takeuchi & Hülse (1993) maintain that no adult has ever developed a convincing capability of absolute pitch recognition. Large-scale surveys in both Japan and Poland by Miyazak et al. (2012) into the occurrence of absolute pitch concluded that commencing music training at an early age, exposure to ‘fixed-do’ (solfège) instruction and training in piano along with a genetic predisposition supports the development of absolute pitch.

3.5 Tuning in *a cappella* singing

When choirs first started singing centuries ago they were unaccompanied and so free to fix the pitch to complement the framework of the music, i.e. to suit the range of the majority of the singers. Once they had their starting note or, more possibly but not as will be argued below necessarily more helpful, the notes of the first chord, their aim was to produce a pleasing sound by staying in tune. They followed the tuning method in vogue at that time. The development of keyboard instruments led eventually to the introduction of equal temperament tuning which is not necessarily the most appropriate tuning for singing *a cappella* music.

3.5.1 Temperaments and tuning

Howard (2007, p. 303) introduced the notion that singers, in this case a vocal quartet:

> 'will drift in pitch with modulation if it tends to non-equal temperament.'

What is being suggested here is that when singers are not accompanied by instruments, just intonation is preferred to the equal temperament to which modern instruments are generally tuned. This is reinforced by Lindley (2014) who cites Zarlino in 1558, Benedetti in the 1650s and Mersenne in 1636 as all supporting the proposition that unaccompanied singers tend towards the '*pleasing sounds*' produced by tuning to just intonation.

Before the 19th century there was no standard pitch, and many of the early pieces sung today have been transposed, so the key may well have been chosen to give a suitable range for each part. Today's composers are most likely to choose the key that offers the specific qualities required by their composition. Ishiguro (2014) discussed the phenomenon of key characteristics by reviewing the writings and opinions of music scholars, scientists and composers of the past 150 years. He concluded that such characteristics are the results of personal interpretation rather than the highly prescriptive views expressed by those he reviewed. Thus, changing the pitch is not necessarily such a bad thing to do but must be taken not as a suitable remedy to the problem of pitch drift but a possible pointer to it – even though this falls outside the area of this research. To ensure accurate tuning when singing four-part *a cappella* choral music, singers are always encouraged to listen to each other. This means tuning their next note from the previous one, most likely from whichever part is singing the root of the previous chord. Howard (2007) investigated the problems of *a cappella* tuning with experiments based around his composition shown in Figure 3.4.

Figure 3.4 Pitch drift tuning exercise where the tied note provides the reference for tuning the next chord (adapted from Howard, 2007, with permission)

Given that unaccompanied singers tune for maximum consonance (i.e. using just intonation) the pitch is likely to drift away from equal temperament tuning. This may seem surprising but can be predicted from Howard's composition above by calculating intervals from the reference note of the first chord in bar 1, the tonic (C_4). From this note the frequencies of the major third (E_4), perfect fifth (G_3) and octave below (C_3) in the chord can be calculated using simple ratios for just intonation and the equal temperament modifiers shown in Table 3.3.

Table 3.3 Ratios to the fundamental in just intonation to equal temperament

Interval	Just intonation	Equal temperament	Difference
Unison	1:1 = 1.000	1.000	0
Major second	9:8 = 1.125	1.123	–0.002
Major third	5:4 = 1.250	1.259	0.001
Perfect fourth	4:3 = 1.333	1.335	0.002
Fifth	3:2 = 1.500	1.498	–0.002
Major sixth	5:3 = 1.667	1.682	0.001
Major seventh	15:8 = 1.875	1.888	0.013
Octave	2:1 = 2.000	2.000	0

As C_4 (middle-C) is tied to the second chord in bar 1 on the alto line, it is sung without a break and so may be used as the reference for the other parts to find their notes; the perfect fourth (F_4) and major third (A_3). In bar 2 the A_3 in the tenor line is tied over from bar 1 and so provides the reference for the perfect fourth (D_3 and D_4) and the major third ($F\sharp_4$), altogether forming a D major chord. The remaining bars are similarly harmonically related to the preceding bar but one tone higher. The results of calculations of the difference between just and equal temperament from Table 3.3 are shown in Figure 3.5 and predicts a drift in pitch, over 13 chords, of up to –120 cents. The actual drift from a performance of Howard's composition is shown in Figure 3.6.

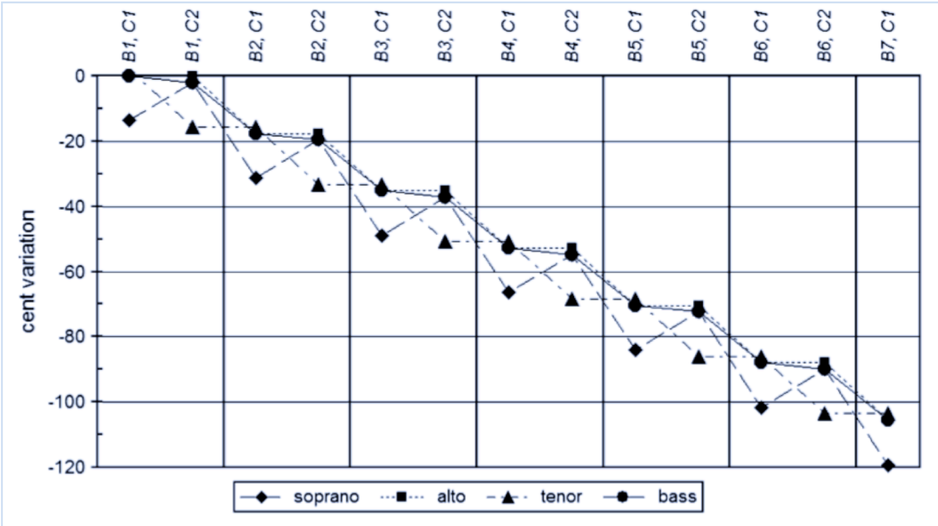


Figure 3.5 Predicted drift in pitch for Howard's composition of Figure 3.4 (Howard, 2007, with permission)

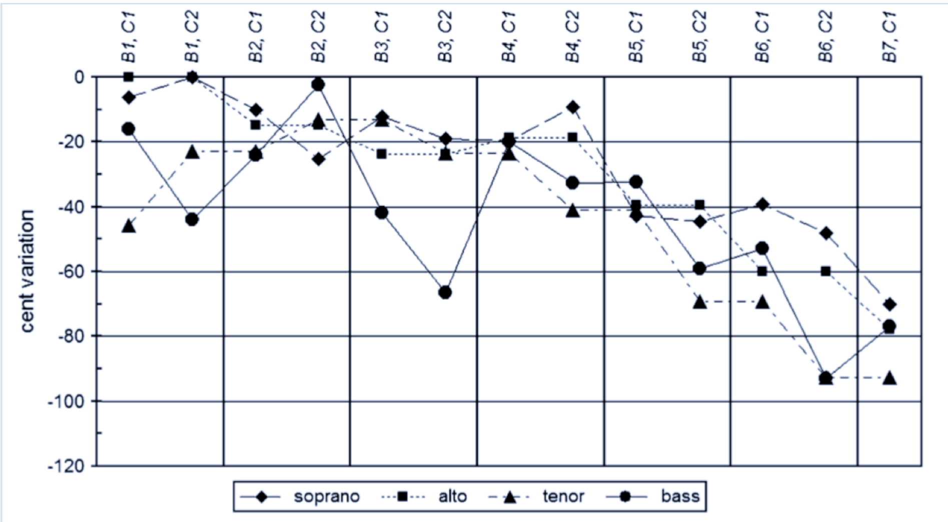


Figure 3.6 Actual drift in pitch in performance for Howard's composition of Figure 3.4 (Howard, 2007, with permission)

After a small drop in pitch at the beginning of bar 2 in line with the prediction, the soprano and alto maintained pitch to within 20 cents until the first note in bar 5 when they dropped a further 20 cents. Similarly, after a poor start the tenor kept to the pitch until the second note of bar 4 when the pitch dropped as predicted. The bass was rather inaccurate until bar 4 after which the pitch steadied. From bar 5 the pitch dropped as predicted although the soprano and to a lesser extent the alto try not to drop any further in pitch. Overall the pitch dropped by 80 cents over 7 bars in-line with the prediction in Figure 3.5.

Howard notes that his recent work to examine some 50 works from the *a cappella* choral repertoire predicts that they will all drift flat, with some more than others. To avoid choirs drifting down as predicted, he recommends the pitch reference to be taken not from the preceding chord but from either an accurately maintained melody line that is kept in tune or by some other overall pitch reference. Howard's predictive pitch drift analysis will be applied to some of the music used in the experiments discussed in sub-Section 5.3.4.

3.5.2 Keyboard support

Many amateur choirs start learning a new *a cappella* piece with the support of a keyboard instrument, which is most likely to employ equal-temperament tuning. Often a score will contain keyboard reduction staves set specifically 'for rehearsal only' purposes, as in the example given in Figure 3.7. Howard suggests that if keyboard support is used in rehearsing *a cappella* music, once singers have learned their individual parts they become 'locked-in' to equal temperament tuning which can cause a dissonance making it harder for the choir to achieve a harmonious sound. This can be further exacerbated by giving a chord from a keyboard just prior to a performance – Howard suggests that giving a single note is preferable to the chord.

However, given this is the case and pitch drift is inevitable, then why do choirs maintain the pitch during some performances in rehearsals but drift in pitch by as much as two semitones (200 cents) on other occasions when singing the same piece of unaccompanied music in the same venue and at the same time of the week? No literature reporting research into why or even just acknowledging that this happens has been found to date.

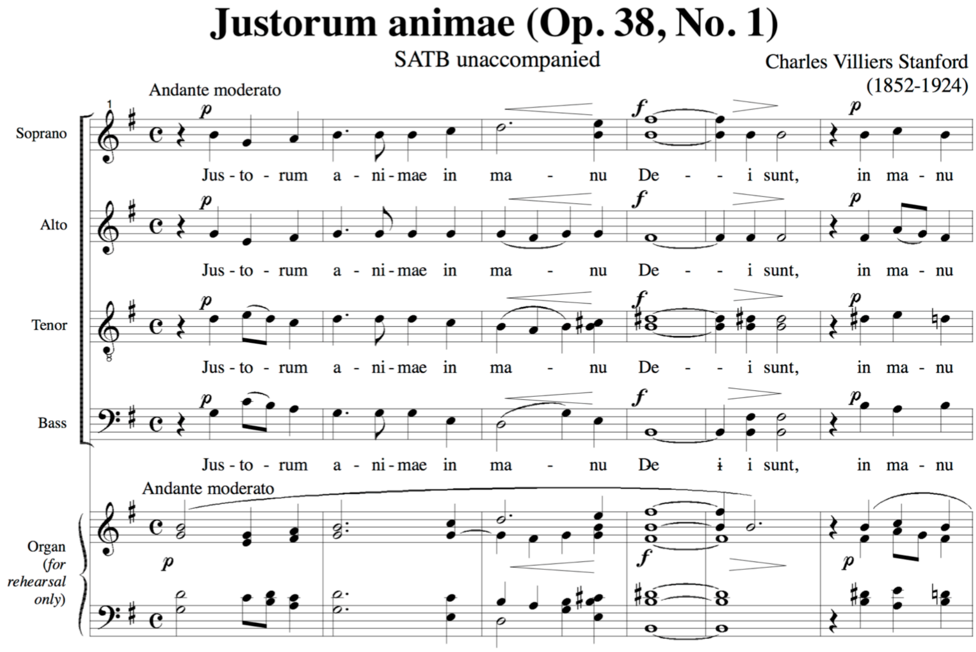


Figure 3.7 An example of an *a cappella* work with a keyboard (organ) reduction 'for rehearsal only'. (Copyright © 1999 by Choral Public Domain Library (www.cpdl.org). Edition may be freely distributed, duplicated, performed, or recorded.)

3.5.3 'Vocal laziness'

Ask anyone involved with choral singing about their major concerns when singing *a cappella* music and their answer is likely to include the avoidance of dropping in pitch, i.e. 'going flat'. Howard and Terasawa have demonstrated that the music may be a possible cause. So, whilst the music may cause the problem it is not always the case and most certainly will not cause the variations in pitch which can occur at different rehearsals. Halsey and Potter suggest various reasons for pitch drift, the former suggesting that key changes appear to help maintain pitch, but there is no literature currently supporting this claim.

In a paper published at the time of writing, Belyk et al. (2018) have suggested that an inbuilt lack of control of the laryngeal muscles that control our voice production may be a contributory factor to pitch drift. They state that even expert singers cannot match the precision of instrumentalists of stringed instruments in precise note production. Given that the listening mechanism is the same in both cases, the fault would appear to lie within the mechanics of voice production. The laryngeal muscles have evolved sufficiently to give humans a vocal-pitch which the articulatory muscles that controls the lips and tongue to produce speech patterns. Their experiments involved 28 participants who described themselves as either 'strong' or 'poor' singers but who had an ability to whistle. The first of two tasks involved participants imitating 45 five-note melodies comprising a synthesised voice with a neutral vowel. Vocal ranges of A_3 to A_4 for females and A_2 to A_3 for males were used. The procedure involved the participant listening to a randomly ordered melody and then singing the melody whilst being recorded. A second task used a set of modified sine waves, from A_5 to A_6, to produce whistling melodies which were then imitated by whistling as in the first task. Their results demonstrated that whistled notes drifted down by ~40 cents while the sung notes drifted down by ~140 cents. Moreover, they observed a consistent bias for the pitch to drift down as the pitch of the note got higher.

Belyk et al. posit that an individual's larynx may have a 'preferred frequency' that requires the least muscular effort to generate. They term this effect 'vocal laziness' (not to be confused with 'lazy' in terms of tired or recalcitrant singers). This is an innate conservation of vocal effort which may cause singers to move the pitch of the sung notes towards the pitch associated with their preferred frequency thus causing the pitch to drift. This confirmed the findings of Pfordresher and Brown (2007) who observed a 'comfort pitch' and the tendency for weaker singers to drift towards this zone demonstrating an inflexibility in the pitch range of such singers.

3.6 Summary

This chapter has reviewed past and current evidence which confirms that pitch drift occurs when singers perform *a cappella* music. Suggested reasons for pitch drifting range from snowy afternoons to the fact that singers tend to pitch using the simple ratios of just intonation rather than the intricate tuning of equal temperament. Whilst snowy afternoons do not appear to be well researched, the evidence regarding the human tuning abilities are well represented. In particular the recent work by Howard (2015) demonstrating possible pitch drifts are due to the composition of the music have been confirmed by performance. Certain *a cappella* works by composers such as Bruckner, which tend to drift in pitch no matter how well-respected the choir, may now be explained. Even a live broadcast from the BBC Radio 3 programme 'Choral Evensong' of Bruckner's *a cappella* piece *Locus iste* dropped in pitch by 50 cents. Interestingly, the choir started the piece 25 cents sharp, which may be a strategy to try to reduce compositional effects that cause the works of Bruckner to drift down in pitch (Howard's results for *Locus iste* are discussed in sub-Section 5.3.4).

This research will consider why, when regularly singing a particular piece of *a cappella* music, the pitch drift tends to differ on each occasion, i.e. worse sometimes but better at other times. The academic research literature discussed above proffers reasons for the causes of pitch drift; the composition, the temperament, the layout of the choir, the acoustic properties of the room, even 'vocal laziness'. There is no doubt these reasons may be causal but if so then the pitch drift should not vary irregularly. If a particular piece drifts by a semitone at one rehearsal, then it should drift by a semitone at all rehearsals as cited by Teresawa (2004). However, anecdotal evidence disputes this, pitch drift does vary between regular performances of the same *a cappella* music. No research or literature either supporting this anecdotal evidence or giving reasons why pitch may drift on an irregular basis can be found.

The next chapter introduces a survey of choral practitioners designed to gather evidence as to whether pitch drift occurs on an irregular basis and, if so, whether it is of concern to the respondents and the strategies they may adopt to resolve the problem. Interviews with four experienced choral conductors follow and the chapter ends with correspondence on the topic from two well-regarded choral composers.

Chapter 4
Pitch drift in choirs

> 'One thing I try never to do is to just say to a choir or a section of it "you're flat" – it's always better to propose the remedy not just complain about the disease.' (John Rutter, 2014)

4.1 Introduction

The aim of this chapter is to report the results of a survey, interviews and correspondence with choral practitioners which will shape the research into directions which may yield evidence as to why pitch drift occurs irregularly at rehearsals.

The chapter opens with details of the design, distribution and data collection of a survey aimed at choral practitioners, including amateur and professional singers and musical directors, to elicit their perception of pitch drift in their own choirs when singing *a cappella* music. It also allowed an insight into the different types of choir that perform unaccompanied music around the world. The results of an analysis of the responses to the survey are discussed. Interviews with four experienced choral conductors are complemented with correspondence from two composers of choral music. The chapter concludes with a summary of the outcomes from the opinions of all those who offered their experience and advice both of leading and singing in choirs of various types. It is acknowledged that respondents may produce different reactions to the questions regarding pitch drift, but it was important in all cases not to lead their replies in any way.

4.2 Questioning choral practitioners

4.2.1 Rationale for a survey

Whilst the existence of pitch drift in *a cappella* Western choral singing is recognised, the reasons why it occurs on an irregular basis requires research for, although a wealth of anecdotal evidence is available, Chapter 3 demonstrated the lack of academic literature on this topic. A survey, which is targeted at a group of practitioners within the desired subject area, can be an efficient way of gaining the opinions of others. The following is a discussion of the design, development and analysis of a survey of choral practitioners into their experience of choirs, rehearsals and pitch drift.

The first stage of this survey was the development of a questionnaire to elicit opinions of choral practitioners. There were three objectives:

- ascertain details about choirs and their singers;
- establish where and when rehearsals take place and an assessment of the acoustic properties of the rehearsal venue;
- gather the respondents' experiences of pitch drift and where appropriate their suggestions as to possible causes and cures.

The results of the survey were used in part to inform the design of a series of experiments to be undertaken by several choirs. These experiments address the research question; namely, possible external reasons for irregularities in pitch drift in *a cappella* singing. External reasons cover environmental factors, choir membership, acoustics – in fact almost anything unrelated to the composition of the music.

Permission for the survey and the resulting experiments with choirs was sought from the Open University Ethics Committee (HREC/2013/1394/Pim/1). The application was given ‘a favourable opinion’ and permission granted to undertake a survey of choral practitioners and a series of experiments with choirs. The Ethics committee, the choral practitioners and the singers in the choirs involved with this research were all assured that any data gathered would be stored securely and rendered totally anonymous before use. All data would be used anonymously and solely for conference presentations, journal papers and reports entirely within the framework of this research.

4.2.2 Development of a questionnaire for the survey

A questionnaire that is to deliver good-quality data needs to be thought about and planned. Following the guidelines of Brace (2008) the principal information sought was defined from the objectives detailed above. Secondary information, required for analysis, was determined and finally a sequence of sections for the questionnaire was mapped. Care was taken only to ask questions which were relevant to the main objectives and not to ask leading questions.

Procedures for preparing the questionnaire for online distribution were taken from Hewson (2003) to ensure that the exercise worked as efficiently as possible. The drawback to ‘internet mediated research’ (i.e. online using a tablet or computer to respond) is that there is less opportunity to gain some knowledge of the participant. With more traditional face-to-face questionnaires, observations of the body language and tone of voice may help to evaluate the responses. Encouragingly, Hewson found that studies made to validate the results of online research compared favourably with those from traditional methods. The procedures below, adopted from Hewson, were followed to maximise the efficiency of the questionnaire.

- Provide explicit and clear instructions to participants as to what was required.

- Monitor information about participants such as their IP address and the date and time of their response in order to detect multiple submissions. In the event, this was controlled by the choice of survey platform, as discussed below.
- Variations in computer platforms and/or internet connection speeds should not affect the involvement of the participants taking the questionnaire.
- Avoid the necessity for any specialist software or hardware knowledge in responding to the questionnaire.
- Pilot the survey to detect any issues before release.

Whilst the use of an online questionnaire might limit the number of responses to some degree due to the technology involved, Matthews (2018) stated that 83% of households in Great Britain (21 million) had internet access in 2013. Reassurance was further gained from a project by the *European Choral Association* – an affiliation of 15 non-profit organisations from eleven European countries – who undertook a study of choral singing in Europe. Their *Singing Europe* research also used an online questionnaire developed by Bartel *et al.* (2015) which was released in July 2013 (a similar time to the questionnaire for this research). Whilst appreciating that some groups of the population would not be reached, the *Singing Europe* research group stated:

> '…it is not possible to reach all singing groups in Europe since we do not know what and where they are…' (Bartel et al., 2015 p. 51)

The reason simply was that no lists of the choirs in Europe existed at that time. Singers in choirs were reached through online networks devoted to choral singing and advertisements. The *Singing Europe* survey was active for 15 months and gathered 4154 completed questionnaires with no repetitions.

4.2.3 A platform for the questionnaire

The *SurveyMonkey*®[1] platform was chosen for this questionnaire as it provided all the tools to design, deliver, store, and analyse the data with the additional advantage of being able to download the data in an *Excel*® compatible format for offline analysis. A subscription to *SurveyMonkey's SELECT®* annual account was purchased. This offered an unlimited number of questions and responses along with an option to customise the survey design including a limited opportunity for branding the questionnaire. Being able to use the well-respected Open University logo was thought important as it lent credibility to this research. Enhanced security and a wide range of analytical features including customised reports were also available. Access to the results was reported as being maintained free of charge once the subscription lapsed but proved not to be the case. In a change to their terms and conditions, *SurveyMonkey* now only allow free access to the first one-hundred responses – a small charge being levied to gain access to all the responses. Fortunately, this was not a problem as the survey was closed and all responses downloaded and backed-up before the one-year subscription expired. For those wishing to respond without access to the internet, or not wishing to take part in an online survey, a paper-based version of the questionnaire was mailed to them along with a prepaid return envelope. In the end only four responses were received in this manner, which were added to the downloaded data at the end of the survey period.

4.2.4 Design and delivery of the questions

The questionnaire, displayed in Appendix 2, opened with a description of the aims of the research and a request for support. Assurances as to the security and anonymity of their responses were also given. The questions followed in three sections.

- Details of the choir – the name, website, gender and age range of singers, genre of music sung (Questions 1–8).

[1] www.surveymonkey.com (accessed 2 December 2016)

- Features of the choir's rehearsals and venue – the time of rehearsals, type of building, acoustic properties (Questions 9–13).
- Questions about pitch drift during unaccompanied singing – whether it happens, when and how it happens, whether the drift is sharp or flat, whether public performances make a difference (Questions 14–20).

This was followed by a question asking respondents about their relationship with the choir, e.g. singer, musical director, accompanist, etc. (Question 21). Finally, a message of thanks for the respondents time was given along with an opportunity for them to leave their name and email address should they want to be kept informed of the research and take part in any future surveys or experiments (Question 22). A guarantee was given that they would only be contacted in regard to this research.

The questions consisted mostly of the multiple-choice list-answers where one or more responses could be selected from a list of appropriate words or phrases. Several questions had a default 'other' choice as a catch-all in case the list did not apply. There was also the opportunity for comments, which was encouraged. The questions which dealt with experiences of pitch drift were necessarily open-ended with boxes for free-text replies allowing the respondents to volunteer as much information as they felt able. Any of the questions could be skipped.

A paper-based version of the questionnaire was piloted with five experienced choral practitioners who were known to the author but had not had any previous contact with the research at that time. Once completed, their responses were analysed and, in the light of their answers and general feedback, certain questions were refined. The questionnaire went live online in mid-August, 2013.

4.2.5 Seeking answers

As with the *Singing Europe* study mentioned above, advertising was seen as essential for the success of this questionnaire. It was soon realised that simple networking, such as word-of-mouth, would not give sufficient numbers. As at least one-hundred answers were considered necessary for significance, a publicity campaign was put in hand. The research website[2], based on the Open University's standard framework is shown in Figure 4.1. It was published through a link supplied by the University's IT Department. A useful feature of the website was the *News* column which was regularly updated to keep visitors informed of progress. To accompany the website a mailbox[3] was created to allow visitors to contact the research team. The research logo, shown at the upper right of the home page was taken from a photograph of an art-work[4] displayed in the Venables quadrangle on the campus of Open University at Milton Keynes.

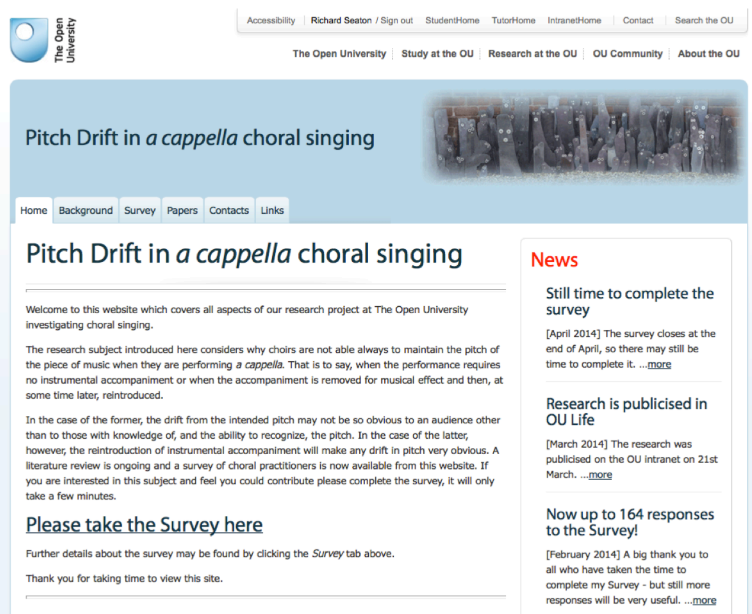


Figure 4.1 Pitch Drift website showing the link to the survey (accessed 1 April 2014)

[2] mcs.open.ac.uk/acoustics/pitchdrift/ (accessed 1 April 2014)
[3] pitch-drift@open.ac.uk
[4] *This land is our land* (2007) by Graham Mills, purchased by the OU Artwork Group in 2008

To further aid publicity, the *Association of British Choral Directors (ABCD)*[5] was approached for assistance with promoting the research at their 28th *Annual Conference* which was held in Oxford at the end of August 2013. They offered a complimentary stand area in their exhibition hall on Saturday 24th August 2013 (see Figure 4.2).

Figure 4.2 Photographs from *ABCD*'s 28th Annual Conference, August 2013

The *ABCD* staff were very supportive of the research and ensured that delegates were informed about and directed to the stand. Various materials and examples of experiments were displayed on the stand. A trifold leaflet was printed for the event and handed-out to delegates (Appendix 3). The leaflet proved very useful when describing the research and acted as an aide-memoir for delegates to complete the survey. *ABCD* also publicised the research on their website, which also included details of the survey. Their support for and interest in this research is gratefully acknowledged.

One visitor to the stand was the then executive director of the *American Choral Directors Association (ACDA)*[6], who kindly agreed to publicise the research in the association's *Choralnet* newsletter during September 2013. This led to several responses from the USA that month. An article appeared at the same time in the *Musical Acoustics Group Magazine* of the *Institute of Acoustics*[7]. During the author's visit to Western Australia

[5] Association of British Choral Directors – abcd.org.uk (accessed 10 July 2018)
[6] American Choral Directors Association – acda.org (accessed 10 July 2018)
[7] Institute of Acoustics – ioa.co.uk (accessed 10 July 2018)

the following month, contact was made with *Voice Moves*[8], Western Australia's major choral association. Their secretary posted details of the research to members which resulted in additional responses. However, not every attempt at publicity was successful. Several emails were sent to the *BBC Radio 3's* programme *The Choir*[9] but no reply was received other than an automated acknowledgement. An email to *Classic FM*[10] was not even acknowledged.

By the end of January 2014 only 72 survey responses had been received. More responses were needed so a decision was taken to contact the *Research Centre for Music Performance as Creative Practice, CMPCP*, which is funded by the UK's *Arts and Humanities Research Council (AHRC)*. The *CMPCP* is an association of academic institutions leading a research programme focussing on live musical performance and creative music-making. The *CMPCP* co-ordinator, Dr David Mawson, was contacted. He suggested that their *Performance Studies Network* (Perf-Stud-Net) e-forum be used to contact members along with the *Musicology-All* e-forum, which might also be useful. Dr Mawson's support to this research is acknowledged. These forums proved extremely useful with the number of responses nearly doubling overnight following publication of messages detailing the survey. An additional request for participants towards the end of March on *OU Life*, the Open University's staff intranet, yielded several further responses. Figure 4.3 shows the number of responses received each month during the survey period.

The survey was closed at the end of May 2014 with a total of 298 responses (this included the pilot and testing) of which 216 were valid, i.e. the response contained full and usable answers. Note that multiple answers from a single IP address were prevented to avoid multiple responses, of which none were apparent.

[8] Voice Moves (WA Inc) – voicemoves.com.au (accessed 11 July 2018)
[9] *The Choir* – bbc.co.uk/programmes/b006tnw5 (accessed 11 July 2018)
[10] *Classic FM* – classicfm.com (accessed 11 July 2018)

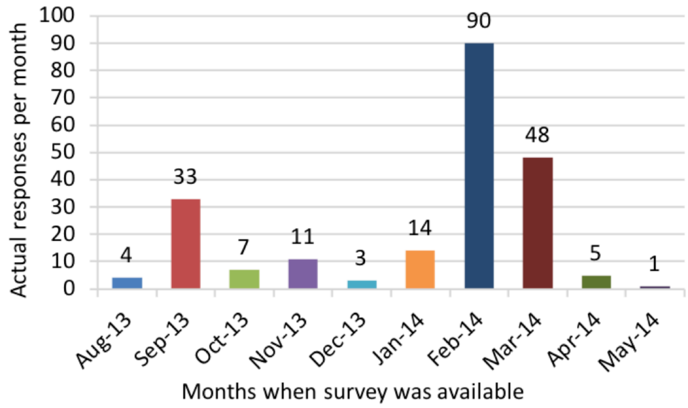


Figure 4.3 Numbers of valid responses by month from August 2013 to May 2014 (total = 216)

4.3 Analysis of the responses

4.3.1 Introduction

The responses to the questionnaire are outlined below. The three sections of the questionnaire asked about the respondent's choir, their rehearsals and venues, and their experiences of pitch drift. The results are split into sub-sections with charts and tables displaying information considered pertinent to this research. Particular emphasis is laid on the section covering pitch drift as the outcomes provided some important information necessary for the design of the experimental stage of this research.

4.3.2 Details about the choirs (Questions 1–8)

The first section of the questionnaire sought details about each respondent's choir by requesting:

- the name and the location (Question 1);
- the choir type and the repertoire sung (Questions 2 and 3);
- the size, including the male/female split, and approximate ages of the members (although these results were found to not be pertinent to the final research) (Questions 4–6);

- the backgrounds of the singers, (i.e. whether they were professional musicians or amateurs) (Question 7);
- an indication of how regularly *a cappella* music was performed (Question 8).

Question 1: Give the name and location of your choir

Where the location was given in answer to Question 1, the majority of responses were received from choral practitioners in the United Kingdom, although aforementioned support from both Australia and the USA yielded some responses, as shown in Figure 4.4. For responses where no location was given the IP address of the participant's Internet Service Provider was analysed to ascertain the probable country of origin.

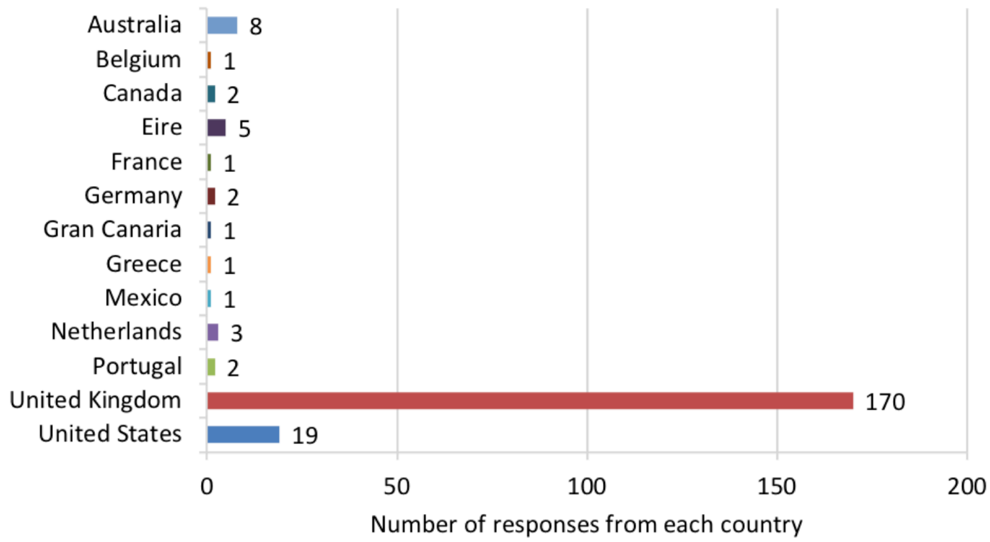


Figure 4.4 Number of questionnaire responses from each country (total = 216)

Question 2: Which description most closely describes your choir?

In Question 2 respondents were offered a choice of choir types shown in Table 4.1. Whilst this list was far from complete (at least 20 different types were found by web searches) the choices offered represented the more popular choir types whilst not being too specific. Regrettably, church choirs were missed off the original list but fortunately the 'other' option gave an opportunity for any choir type to be included and a comments section allowed for further details. (However, omitting church choirs from the list did lead to some enlightening comments.) It was hoped no respondent would feel unable to complete the questionnaire due to their choir type not being listed.

Table 4.1 The original list of five choir types plus 'Other' used in Question 2 (total = 216)

Choir type	Responses
Barbershop or Sweet Adelines	8
Chamber choir	70
Choral society	35
Community choir (adult, children or mixed)	46
Vocal group	20
Other	37

A chart displaying choir types that includes a category for church choirs is shown in Figure 4.5. There were 18 church choirs mentioned in the 'other' category which are placed in this omitted category. The remaining 19 choirs in the 'other' category were able to be placed under one of the original categories of Table 4.1 from the given details of their choir. The numbers of choirs under each heading are shown in brackets in Figure 4.5. It may be seen that chamber choirs represent the largest number of choirs in the survey with 78 responses. Community choirs had the next highest representation with 49 responses. The rise in popularity of this choir type is due in part to the publicity generated by the BBC's reality television programme series *The Choir* hosted by the choirmaster Gareth Malone between 2007 and 2011[11]. The variation and numbers of choir types met expectations and proved useful in deciding which types of choir to approach for the research experiments.

[11] En.wikipedia.org/wiki/Gareth_Malone (accessed 11 July 2018)

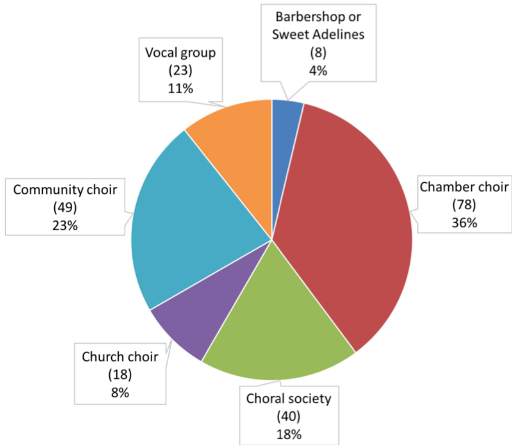


Figure 4.5 Revised list of six choir types which includes 'church choirs', omitted from the original survey (total = 216)

Question 3: The repertoire of choirs

The list of musical genres forming the repertoire of the choirs represented by their choir types was developed from a web-search. Most respondents reported their choirs singing all of the genres, listed at the bottom of Figure 4.6. However, Barbershop and Sweet Adelines choruses reported singing just two genres – early 20th century and modern music – but always performed *a cappella*. Renaissance music (often sung unaccompanied) formed a higher proportion of the repertoire of chamber and church choirs. Community choirs and vocal groups reported singing modern music whilst choral societies tended to prefer music from the baroque, classical and romantic genres. This was useful information as certain genres such as baroque, classical and romantic tend to be sung accompanied whereas renaissance, early 20th century and to a degree, modern genres are often sung unaccompanied.

A concern was expressed that respondents to the questionnaire would self-select themselves to complete the survey because they experienced pitch problems when singing *a cappella* music. However, given the range of genres sung, with only just over half the repertoire likely to be sung *a cappella*, a reasonably balanced set of responses could be assumed from this survey.

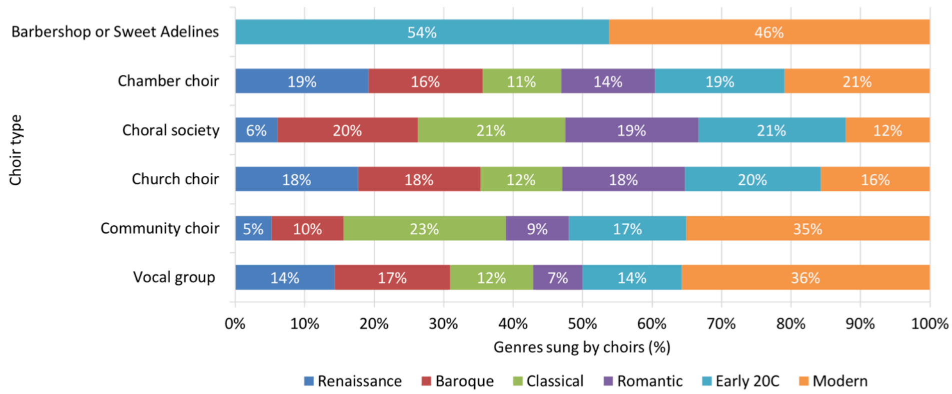


Figure 4.6 Repertoire of each choir type in terms of the percentage of each the six genres shown which are performed by the choir types (total = 216)

Question 4: The demographic of singers

The ages of singers in the respondents' choirs were requested in Question 4. Figure 4.7 shows the percentages of singers, from 213 responses, in each of the four suggested ranges; under 18; between 18 and 29; 30 and 49; and over 50. The responses represent 9007 singers.

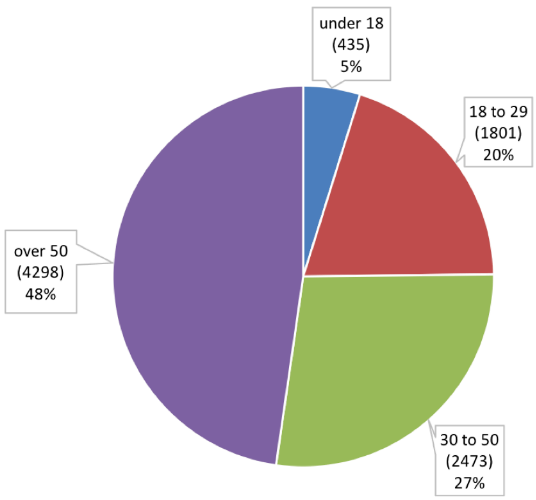


Figure 4.7 Age ranges of singers in respondents' choirs (total = 9007)

Whilst the results from this question were not in the end used by this research, they are presented here for use by others interested in the age demographics of choirs.

Question 5: Female singers in choirs

Questions 5 asked about the distribution of female singers across the four voice parts.

Question 6: Male singers in choirs

Questions 6 asked about the distribution of male singers across the four voice parts.

The combined results to the two questions (61.5% female to 38.5% male) are given in Figure 4.8 and represent 9461 singers calculated from the totals given within the 213 responses to this question.

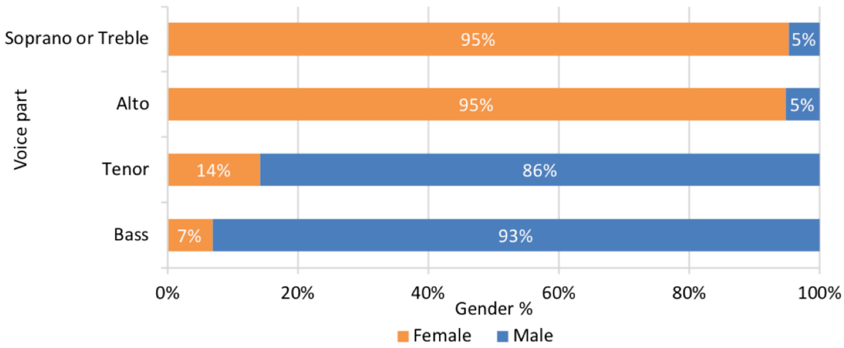


Figure 4.8 Gender (female/male) distribution across the four voice parts (total = 9461)

Note that the discrepancy between the total number of singers given in Question 4 of 9007 and the two sets of responses reported here of 9461 could not be explained from the questionnaire data. Sixty-nine of the 216 responses reported different numbers of singers between these two questions and the earlier question on age.

The numbers of singers in each voice part, which were also obtained along with the above demographics, are shown as percentages in Figure 4.9. The sopranos include boy trebles who attend church and youth choirs. Male altos and female tenors and basses are also found in many choirs. Barbershop and Sweet Adelines choruses have a different arrangement of the four voice parts – tenor, lead, baritone and bass for both groups, with Sweet Adelines singing an octave higher than Barbershop choruses.

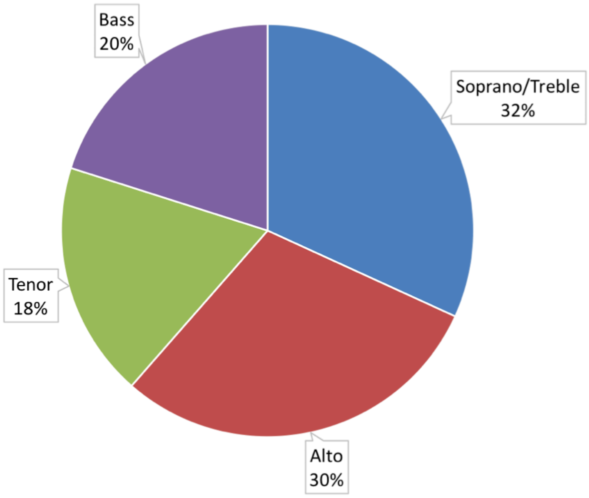


Figure 4.9 Male and female singers in each voice part (total = 9461)

As before, whilst the results from this question were not used within this research, they may be of use to others interested in the composition of choirs.

The results of Questions 4, 5 and 6 were combined in Figure 4.10 which shows the average number of singers in each choir type. In reality the numbers varied greatly, particularly with the Barbershop and Sweet Adelines choruses which would be expected to be no bigger than vocal groups but here includes a European Sweet Adelines chorus with 90 singers!

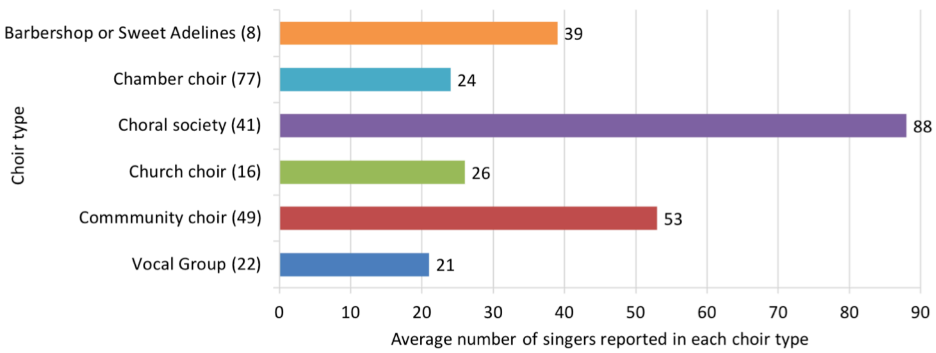


Figure 4.10 Average numbers of singers in each choir type (total = 213)

Question 7: How would you best describe your singers?

Question 7 looked at the experience of singers in the respondents' choirs. This is an important question as the choirs with auditioned singers might be expected to experience less pitch drift than those choirs who do not audition. The four categories of singers in the question were: professional, experienced, auditioned and unauditioned. Unfortunately, this list was not entirely satisfactory as it failed to differentiate between auditioned and unauditioned singers in the 'professional' and 'experienced' categories. However, these singers were assumed to be auditioned as they are most likely to apply to choirs with reputations for high quality performance which would doubtless have auditions. Figure 4.11 shows how these four categories of singers were allocated within each of the various choir types.

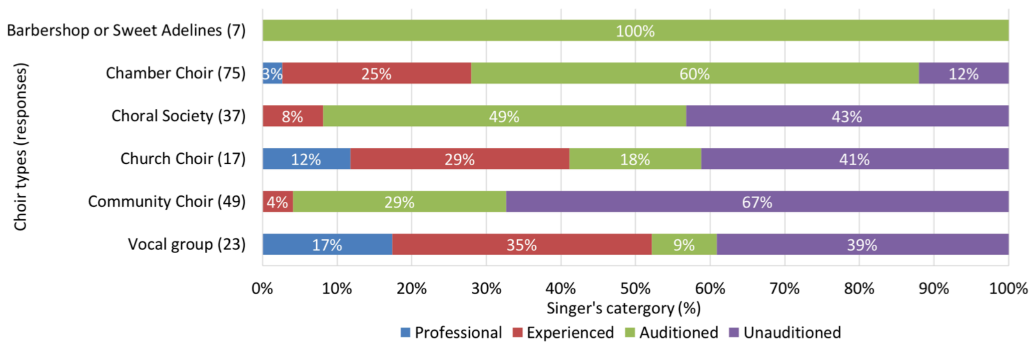


Figure 4.11 Categories of singers by choir type (total = 209)

All choir types, although not all choirs, were reported as having a policy of auditioning singers. The Barbershop and Sweet Adelines choruses always audition their singers which, given the complexity of their close-harmony *a cappella* repertoire, helps to ensure the proficiency of new singers. The majority of other choir types tend to audition apart from community choirs where respondents reported auditioning their singers in a minority of cases. To reinforce this case the aims of the Salvation Army's guide to setting up community choirs is:

> 'to provide a place where people can come an enjoy singing, regardless of their ability'[12]

The possibility that choirs with more experienced auditioned singers experience less pitch drift will be discussed in Chapter 7.

Question 8: The percentage of a cappella music sung by choirs

The final question in this section of the questionnaire asked for the approximate percentage of unaccompanied music sung by the respondents' choirs. This is a useful question as the results should inform the research as to which choir types would be best to approach to undertake the pitch drift experiments involving *a cappella* music. The results shown in Figure 4.12 are categorized by choir type.

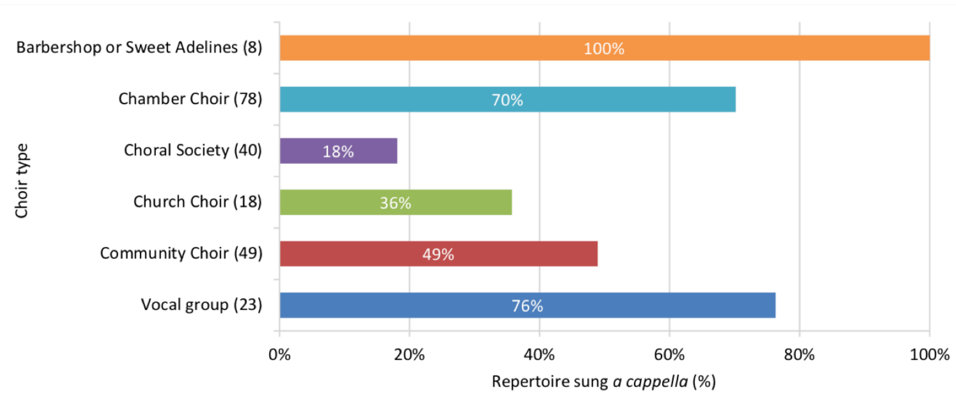


Figure 4.12 The percentage of a cappella music sung by type of choir (total = 216)

As outlined in the previous section Barbershop and Sweet Adelines choruses (average 32 singers) only sing unaccompanied music, confirmed by the responses in Figure 4.12. Vocal groups (average 24 singers) and chamber choirs (average 25 singers) also sing a high percentage of *a cappella* music as this reduces the need for instrumental support when rehearsing and performing public concerts. Most churches have a keyboard instrument to support congregational hymn singing and can also support their choir (average 26 singers), should they be fortunate enough have one. Choral societies (average 88 singers) mostly use instrumental support both in rehearsals and public performances applicable to their

[12] www.salvationarmy.org.uk (accessed 8 October 2018)

repertoire, only singing *a cappella* music occasionally. Finally, given their abilities and larger sizes, community choirs (average 53 singers) will usually offer some instrumental support. Based on the above findings the choir types to approach to take part in this research were Barbershop and Sweet Adelines choruses, vocal groups and chamber choirs. However, no choir type would be ruled-out, as long as they were prepared to sing *a cappella* repertoire for this research.

Summary of Questions 1–8

This completes the first eight questions of the questionnaire which covered details about the respondent's choirs. The most important outcome for this research was to discover which choir types were most likely to sing *a cappella* music. This would be a necessary requirement for all choirs taking part in the experiments covered in Chapter 5 and knowing which choir types to approach was helpful. The response also revealed the most popular choir type to be the chamber choir which typically had between 17 and 40 singers, which would be a sufficient number of singers to ensure significant results from the experiments. Whilst interesting to note for reference purposes, the demographics of the choirs presented here were not used but may be of interest to other researchers in the field of choral singing.

The next section deals with the choirs' rehearsals, providing useful information regarding when and where choirs rehearse. Again, this is an important section as the experiments were planned to be undertaken by choirs at their rehearsal venues.

4.3.3 Concerning the venues and rehearsals (Questions 9–13)

The second section of the questionnaire sought details about the rehearsals of each respondent's choir by requesting:

- a brief description of the venue where the choir rehearses (Question 9);
- which day(s) the choir rehearses (Question 10);

- an assessment of the acoustics of the rehearsal venue (Question 11);
- whether the choir performs in the same venue as they rehearse (Question 12);
- whether the choir rehearses in parts, stand or sit to sing, use *tonic sol-fa* tuning, sing with or without scores and incorporate movement in their singing (Question 13).

Question 9: Where does your choir normally rehearse?

This question asked respondents about where their choir normally rehearsed. They were asked to select the most appropriate answer from a prepared list which included:

- a room (e.g. residential, office, classroom, etc.);
- a small hall (seating fewer than 200);
- a large hall (seating more than 200);
- a modern church building; a traditional parish/country church;
- a cathedral or minster-sized building;
- or ‘other’ (with a description).

These venues are shown, along with the responses, as a pie chart in Figure 4.13. Although 16 respondents used the ‘other’ option it was possible from their information, to interpret the description of their venue to one of the six categories listed above. Seven respondents failed to answer this question.

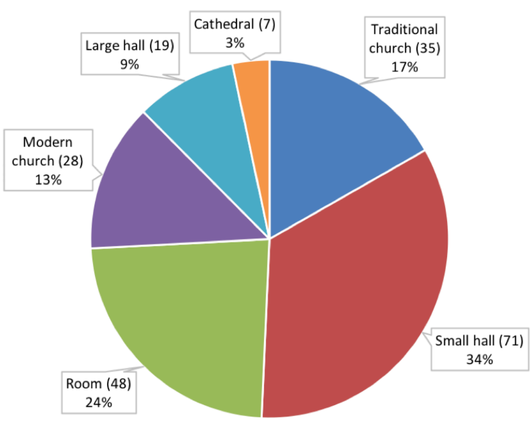


Figure 4.13 Venues used by choirs for rehearsals (total = 209)

Question 10: Practical details about choir rehearsals

Question 10 asked when in the week choirs meet for rehearsal, the time they start and the length of the rehearsal. Again, looking forward to the experiments, it was considered useful to discover the choir types which rehearse regularly over a reasonable period, so that any interruption which may be caused by the experiments may be tolerated by the singers and musical director.

The day of the week on which the choirs rehearse may affect pitch drift due to increasing tiredness through the working week so an opportunity to determine which days of the week choirs commonly rehearse was taken. These are shown in Figure 4.14 for choirs practising on single days in each week. Some church and educational choirs rehearse every day but, as they represented under one percent of choirs, they are not shown on the chart. Monday was reported as being the most popular night followed by Thursday and then Tuesday. Saturdays and Sundays were popular with church and educational choirs.

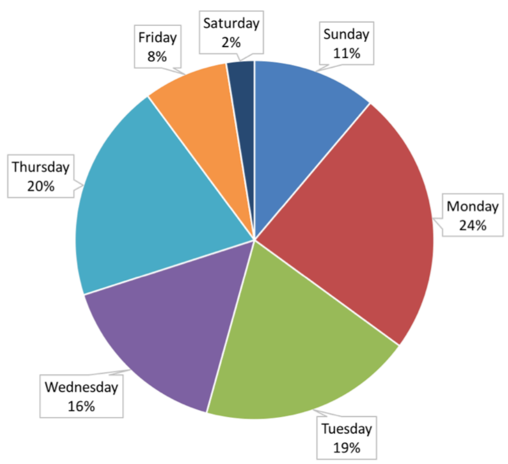


Figure 4.14 Rehearsal days for choirs (under 1% reported as rehearsing every day) (total = 197)

If choirs rehearse in the day-time as opposed to evening there may be a difference in pitch drift as possibly the singers are less tired. Thus, the start times and lengths of rehearsals were requested. Figure 4.15 shows the rehearsal times which indicates that the majority of choirs rehearse in the evening starting between 19:00 and 20:00 hours.

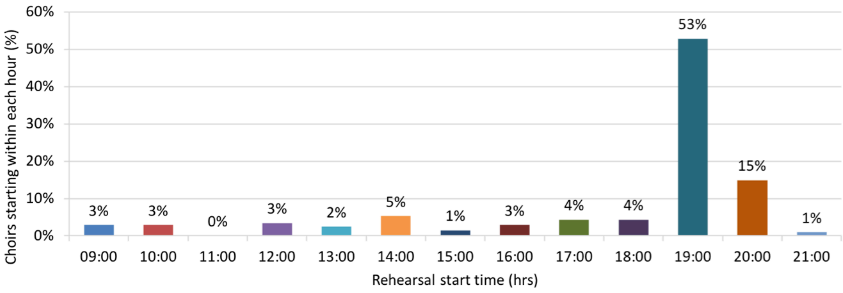


Figure 4.15 Popularity of rehearsal times, shown in one-hour time-slots (total = 206)

On average rehearsals were 2.0 hours in length with a standard deviation of 0.7 hours meaning the majority of rehearsals last between 1.2 and 2.7 hours. The shortest rehearsal period reported was half an hour, whilst the longest was 4.5 hours (with no apparent break!).

Question 11: Acoustic properties of the rehearsal venues?

Alongside the description of the venue, Question 11 asked respondents to estimate the dominant acoustic property of their venue as far as they were able. Five categories, ranging from 'no reverberation (dry)' through to 'very reverberant (wet)' were listed and the responses are shown in Figure 4.16.

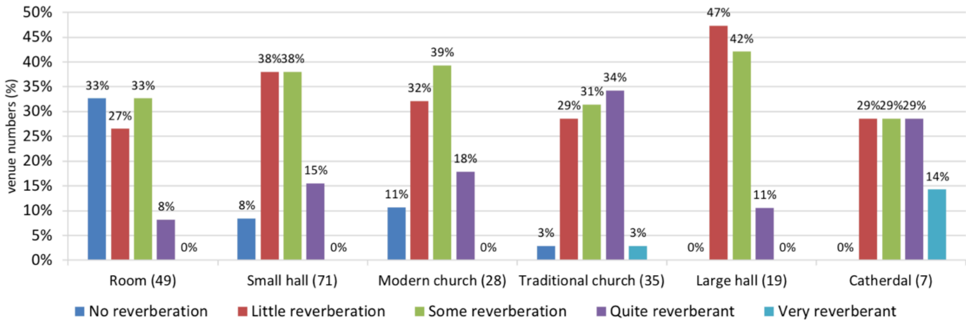


Figure 4.16 Estimated acoustic properties for each type of rehearsal venue used by choirs (numbers of each type of venue shown in brackets, total = 209)

Sixteen rooms were reported as having no reverberation along with one traditional church (slightly surprising). On the other hand, only one church and two cathedrals were described as very reverberant. This maybe because the choirs really use a rehearsal room within the building rather than the space reserved for worship (this is usually the case). Of the remaining three venue types the large buildings were, as expected, reported as being the most reverberant. In hindsight, respondents may have found it difficult to differentiate between five categories, but it was still a useful exercise to obtain these estimates of reverberation for consideration later in the research.

Despite this question seeming somewhat difficult for respondents to answer without having the necessary background, Howard and Moretti (2009, p198), in their research into the suitability of religious buildings in Venice for public performances, found a good correlation between the subjective impressions from audience questionnaires and the acousticians' measurements of the acoustic properties of the buildings. From their experience it is apparent that a wide range of people are able to provide reliable and significant information regarding the acoustic properties of buildings.

Question 12: Public performances

Question 12 asked whether the respondents' choirs perform to the public in the same venue as used for their rehearsal. The responses indicated this is not generally the case with only 15% of respondents' choirs performing where they rehearse, of which two-thirds were church choirs.

Question 13: Behaviours of choirs at rehearsals

Question 13 was a multiple-choice question that investigated the behaviours of choirs during rehearsal with the aim of investigating whether pitch drift is affected by differing practices such as sitting, standing, singing without scores, etc. The choices are listed in Figure 4.17 along with the responses.

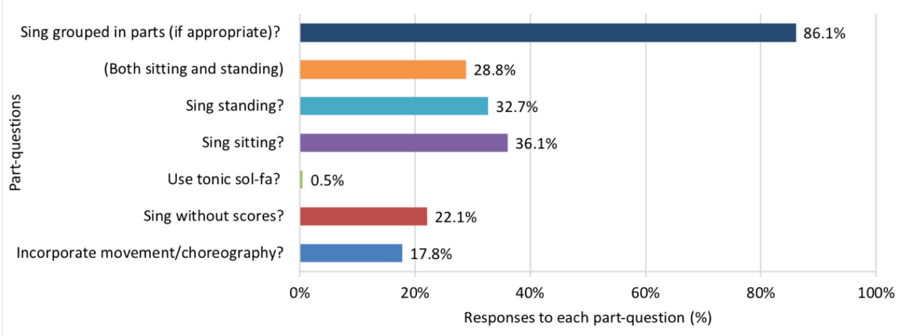


Figure 4.17 Behaviours of choirs during rehearsals (total = 208)

Comparisons of the data extracted from the responses regarding whether choirs rehearse sitting and/or standing allowed an estimate of the numbers of choirs who reported rehearsing both sitting and standing (quite usual in amateur choirs). This figure (28.8%) was added to the results shown in Figure 4.17.

Summary of Questions 9–13

This second section of the questionnaire concentrated on rehearsals. Choirs often have to rehearse in what may be thought of as inappropriate places with difficult acoustics. However, as Question 12 revealed, only 15% of the respondents' choirs both rehearse and hold public performances in the same space, so the acoustics of the rehearsal room should not interfere with public performances. Start times and even days of the week may have some bearing on pitch drift; the next set of questions in the survey asked respondents about their experience of pitch drift in the choirs with which they were associated.

4.3.4 Experiences of pitch drift (Questions 14–20)

The third section of the questionnaire asked respondents to use their own experience and perception to answer a series of question about pitch drift when performing unaccompanied music in rehearsals and public performances. (Note that Questions 15–20 are predicated on the response to Question 14.)

- an estimate of the occurrence of pitch drift in the respondent's choir (Question 14);
- the direction of the pitch drift (Question 15);

- a notion of the time in the rehearsal when pitch drift occurred (Question 16);
- the degree of concern caused by pitch drift (Question 17);
- a request for respondents to suggest why pitch drift happens (Question 18);
- suggested repertoire which might be prone to pitch drift (Question 19);
- a comparison of pitch drift in rehearsals and public performances (Question 20).

Question 14: Occurrence of pitch drift in a cappella *singing*

Of the 199 responses received to Question 14 regarding the occurrence of pitch drift, only 13% of the respondents reported pitch drift never or only rarely occurred. The majority (48%) reported occasional occurrences whilst 39% reported that pitch drift happened on a regular basis. These results are shown in Figure 4.18. Of the 75 respondents who reported that the pitch drifted regularly, 34 were in choirs where singers do not audition, 35 from choirs who do audition with just 6 from professional or experienced amateur singers (also assumed to audition). No respondent admitted to professional singers experiencing the pitch drifting regularly. However, five respondents in this category did admit to pitch drift occurring occasionally.

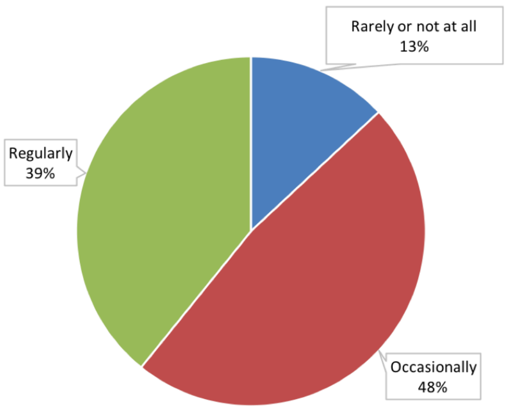


Figure 4.18 Reported occurrence of pitch drift (total = 199)

Question 15: In which direction does the pitch move?

The response to Question 15 regarding the direction of pitch drift in the respondents' choirs is shown in Figure 4.19. Despite this questionnaire focussing on pitch drift in *a cappella* singing 13 respondents failed to answer this question.

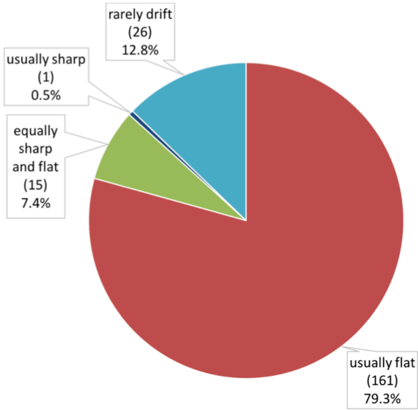


Figure 4.19 Responses to direction of pitch drift (total = 203)

If the 26 respondents who stated that their choirs rarely drift are discounted, then Figure 4.20 shows an overwhelming majority of choirs (91%) who drift down in pitch.

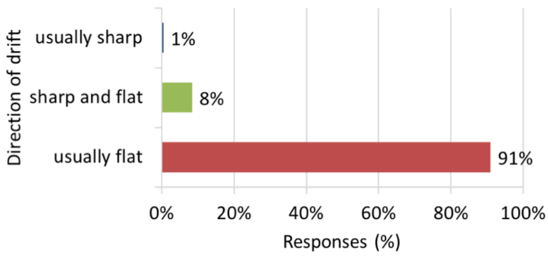


Figure 4.20 Reported direction of pitch drift (total = 177)

There have always been suggestions that choirs are more likely to go down in pitch rather than up, making this result extremely significant. However, it may be argued that this result comes from the experience of those respondents who have chosen to complete the questionnaire because they experience their choirs drifting down in pitch, and that this cannot apply to all choirs. Furthermore, there is no indication as to how the participants in this survey perceive pitch drift or how they may react to it. Given that one of the fundamental issues with choirs singing *a cappella* music is pitch drift (Howard, 2015, p. 126) and that this survey was targeted to choral practitioners, credence is given to the responses to these questions in that the respondents understand the term pitch drift and have applied their experience accordingly to these answers. Thus, the outcomes to this question demonstrate a very significant possibility that any choir is more likely to drift flat rather than sharp in pitch when performing *a cappella* Western choral music.

Question 16: When in the rehearsal does pitch drift?

Having established that pitch drift occurs it was thought useful to discover when in the rehearsal it occurs. From the 176 replies to Question 16, 86% reported that the pitch drifted at any time in the rehearsal. Ten per-cent suggested it happened early on in the rehearsal with just 4% stating it occurred towards the end. Thus, there is no significant evidence that pitch drift is worse either because choirs are warming-up at the beginning of a rehearsal or getting tired towards the end, simply that it happens.

Question 17: Choirs' concerns about pitch drift?

The responses to Question 17 as to concerns about pitch drift indicate that just over half (51.4%) of the respondents were concerned as shown in Figure 4.21. However, a large minority either had no concerns or chose not to comment about pitch drift. This lack of concern may well demonstrate a pragmatic view of the respondent, in line with Potter[13] who suggests that the majority of any audience may not be overly concerned or even appreciate pitch drift had occurred in an *a cappella* public performance.

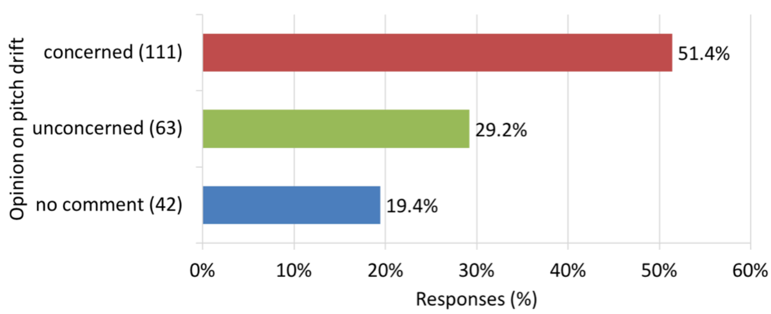


Figure 4.21 Concerns expressed regarding pitch drift as a percentage of replies (total = 216)

[13] Refer to the Literature Review, Chapter 3, sub-Section 3.2.2

Of the 111 respondents who were concerned about pitch drift the majority (57.7%) stated the problem occurred too often. Of the remainder, 23.4% reported that the pitch drift was considered severe with a further 18.9% reporting it being both often and severe, see Figure 4.22. All the reports regarding the existence of pitch drift are assumed to be from rehearsals as that is what the questionnaire requested. Choirs spend most of their time singing together in rehearsals and this is where the experiments that support this research will be based.

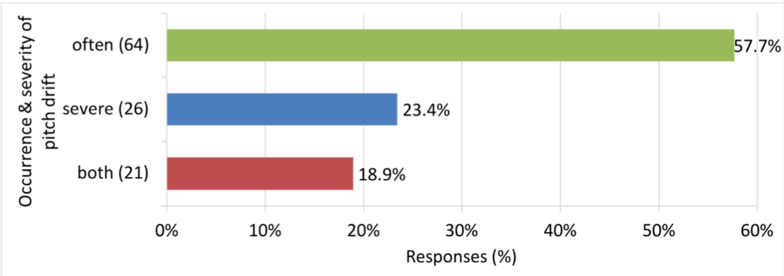


Figure 4.22 Pitch drift ratings by those concerned about pitch drift (total = 111)

The concerns regarding pitch drift can be combined with the earlier answers of the estimates of the acoustic properties of the choirs' rehearsal venues to see if there is any correlation between pitch drift and rehearsal venues. Figure 4.23 shows that the severity and occurrence of pitch drift does not appear to vary greatly with the acoustic property of the venue.

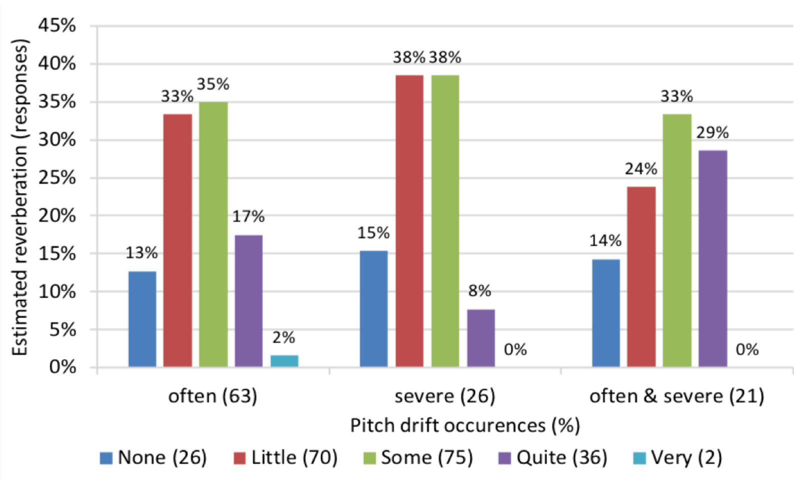


Figure 4.23 Pitch drift shown against the acoustic properties of the rehearsal venues (total = 209)

There is a slight but not significant rise in reports of pitch drift occurring often and being severe in the case of venues with a more resonant acoustic, i.e. large churches and halls. Otherwise, the results are similar for all other venues; i.e. some, little, or no reverberation. These similarities demonstrate that the acoustic properties of the venues used by the survey respondents appear to make little difference to pitch drift when choirs are rehearsing although this finding is not necessarily the case in general. This result will be compared with the acoustic properties of the venues used by the choirs who will take part in the research experiments to determine whether pitch drift is affected by the acoustic of the rehearsal venue. Of course, for a public performance the acoustic properties of the venue can make a huge difference to the experience of both the audience and the choir in terms of blend of voices, etc., whilst ignoring any pitch drift effects. What is more, the exhilaration of a performance may affect pitch drift, which is one reason why the research will concentrate on the regular rehearsals of choirs and will not include any public performances.

Question 18: Why does pitch drift occur?

In Question 18 respondents were asked for possible causes of pitch drift. The most popular reasons may be found in the word cloud[14] of Figure 4.24.

Figure 4.24 Word cloud showing popular words associated with the causes of pitch drift. Note the most popular words 'pitch' and 'drift' were deleted to avoid overwhelming the cloud

[14] www.wordle.net (accessed 26 February 2018)

Word clouds distinguish words that appear most regularly by text size. In this case the words were taken from the free text responses to the question asking respondents to give their opinions as to why pitch drift occurs. The most commonly suggested causes of pitch drift along with the percentage of responses are shown in Figure 4.25.

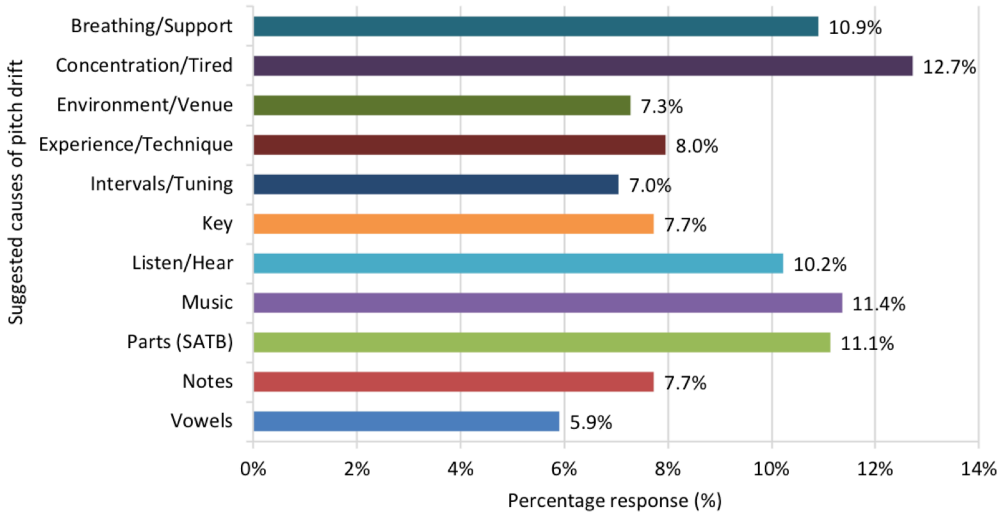


Figure 4.25 Most popular causes of pitch drift suggested by respondents (total = 440)

The most frequent reason given for not maintaining pitch was lack of concentration and/or singers being tired. With over 70% of choirs rehearsing at or after 19:00 hours (i.e. in the evening) it might be reasonable to suppose that during a two hour rehearsal, concentration and fatigue might well become issues. Whether this would lead to the irregular pattern of pitch drift at rehearsals is arguable but will be taken into consideration in the design of the experiments covered in Chapter 5.

As summarised in Section 1.1, the motivation for this research is to establish why pitch drift varies in regular rehearsal performances. Several causes of pitch drift for any particular piece was suggested by the respondents including the music, keys, intervals and venue, all of which are the same at each rehearsal. This is not to imply that they are not in any way contributory factors of pitch drift, but that their effects would be expected to be similar each time the choir performs the same piece in the same venue. Singing techniques should improve with practice (or at least get no worse) although the occasional reminder regarding breath control and watching the musical director can do no harm. The musical key is cited as causing pitch drift with some pieces and that changing the key may lead to a reduction in pitch drift. This reinforces the experience of Halsey in sub-Section 3.2.1. Nevertheless, it fails to provide a reason why the pitch drift changes from rehearsal to rehearsal when the key is kept the same, or if the pitch always improves by the same degree when the new piece is performed in the new key.

Breathing is closely allied to both tiredness and technique. Singers have to remember to intake a breath before they start singing – and not wait for the downbeat – a common complaint voiced by musical directors. Singers must be expected to look ahead in the music so as to be aware of places within the work where breaths may be taken (some musical scores provide breath marks for this purpose). Sub-Section 2.3.6 explained that a constant and controlled supply of air is necessary for formation of a sung note. Should the singer be suffering from tiredness, then both physical and mental control of the voice may be affected. Lack of confidence may mean the singer is unsure of the pitch of the next note to be sung, either from want of preparation or lack of singing ability, making the note less likely to be sung at the correct pitch. Intriguingly, two respondents mentioned mouth-shape could affect the pitch. This is a good point and is in line with the outcomes of research by Sundberg and Skoog (1997) who found that the pitch accuracy of certain vowels at higher notes could be improved with a wider opening of the jaw. This may be linked to tiredness and concentration as well as breath control.

The importance of hearing and listening in maintaining pitch was stressed by respondents. This is supported by the literature review in sub-Section 3.3.1. The acoustic qualities of the venue may affect the ability of singers to listen to each other, but as discussed earlier does not appear to be a direct cause of pitch drift. An assumption, not shown in Figure 4.25, that standing is more likely to maintain pitch has not emerged from the survey. Results show that 71% of choirs who stand to sing experience regular pitch drift whereas 77% of choirs that sit to sing experience the same problem indicating that posture does not have a significant effect on pitch drift. However, many sources express the need for good posture, whether standing or sitting, to ensure the diaphragm can work well and allow good intakes of air into the lungs. However, this is likely to produce a fuller sound rather than specifically reducing pitch drift. The reference to [voice] parts, (e.g. SATB) was to be expected. There is a possibility that a voice part may cause the pitch to drop due to the composition of the music introducing a note which is difficult to pitch. Also, there may be a possibility that singers within particular parts may have an effect if they have the root note.

Question 19: Suggestions for repertoire considered likely to drift in pitch

Question 19 was seeking to learn of repertoire that respondents considered likely to drift in pitch. It was hoped that certain pieces might stand out as being particularly troublesome, and hence be avoided in the experiments. There were 118 responses received with variety of suggestions as to music that has caused pitch drift with choirs. However, the responses 'Anything *a cappella* actually.', and 'With this choir, everything!' did seem to sum up the situation regarding pitch drift rather well if not taken too seriously. On a more serious note music set in the key of F Major was mentioned more than once and will be explored further in the next section. The composer who caused the most concern was Anton Bruckner with his well-known *Motets*[15], which appeared to cause pitch problems with many choirs. (Reference to Bruckner's *Os justi* causing pitch drift was made in sub-Section 3.2.3.)

Question 20: Does pitch drift differ when giving a public performance?

There has always been anecdotal evidence that pitch drift is less problematic in public performances than in rehearsals. Given that most amateur choirs undertake few public engagements compared with rehearsal performances (typically ten rehearsals to one public

[15] en.wikipedia.org/wiki/List_of_motets_by_Anton_Bruckner (accessed 8 October 2018)

performance) there are fewer opportunities for comparison. Hence the reliance on rehearsal data in this survey and in the subsequent research. In this question respondents were asked whether pitch drift was more or less likely to occur in a public performance. Figure 4.26 shows that just under two thirds (64%) of the respondents reported that pitch drift was less obvious or unlikely to occur in a public rather than in a rehearsal performance. Nearly a third (29%) reported no improvement, but this includes those choirs who are unlikely to drift anyway. Seven respondents stated that the pitch drift was worse in public performances, which was most unexpected. Finally six respondents reported pitch drift to be unimportant, which agrees with Potter (sub-Section 3.2.2).

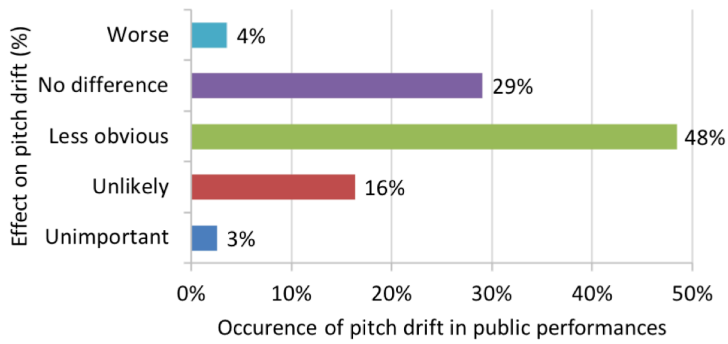


Figure 4.26 Effect on pitch drift of singing in public performances compared with singing in rehearsals (total = 196)

Since this research is looking specifically at performances at rehearsals the reason for this change during public performances is outside its scope. However, it hoped that understanding why pitch drifts during rehearsals will lead to improvements in public performances.

Summary of Questions 14–20

Questions 14–17 produced three significant results. Firstly, there was overwhelming evidence that the choral practitioners responding to the survey believe that pitch drift does occur in most non-professional choirs when singing *a cappella* music. Secondly, the pitch tends to flatten rather than sharpen. Finally, despite anecdotal evidence to the contrary the acoustic properties of the rehearsal rooms does not appear to have a significant effect on pitch drift. The opinions in Question 18 as to why pitch drift occurs proved very useful. Question 19 suggested repertoire that causes problems with pitch drift which supported findings expressed elsewhere in this thesis. Finally, Question 20 confirmed anecdotal evidence that choirs suffer less from pitch drift in performance than rehearsal. The causes are outside the remit of this research but this result may be of interest and use to others working in this field.

4.3.5 About the participants (Questions 21–22)

Question 21: What is your musical relationship with your choir?

The penultimate question (Question 21) of the survey asked participants to choose from a list the option which best described their musical relationship with their choir. The options included 'Other' (with a request for a description) and are shown along with the results in Figure 4.27. Nearly the same number of choral directors as singers completed the survey which provided a useful balance. Comparisons of the results of the other questions between these two groups were very similar and so it was decided to combine all the results together to give an overall view of pitch drift in *a cappella* singing. This included the roles given under the 'Other' option which covered choir administration and teaching.

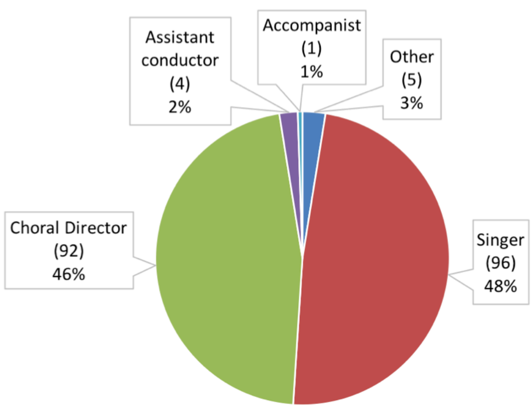


Figure 4:27 Musical roles of participants in the survey (total = 198)

Question 22: If interested, please leave your details

There were 134 respondents who submitted email addresses in order to declare an interest in this research and to receive further information in the future. These respondents will be kept informed of the progress of this research in due course.

4.3.6 Summary of the survey

Despite the slow uptake at the start, the survey proved a success once appropriate mailing lists were accessed. There was a reluctance to make access to the survey too wide through the use of social media as it was required to be targeted specifically at choral practitioners. Over 200 quality responses were received and have been detailed above. The information provided invaluable support in the development of the experiments discussed in the next chapter.

Whilst the survey provided a useful view of a wide range of choral practitioners more in-depth responses were felt necessary. The following section introduces the results of interviews with four choral conductors and correspondence with two choral composers.

4.4 Interviews and correspondence

The survey proved useful in confirming several possible causes that may contribute to pitch drift. However, before moving to the experimental phase of the research, in-depth interviews were undertaken with four experienced choral conductors who work with both professional and amateur choirs in the United Kingdom. Additionally, correspondence was entered into with two of the UK's leading choral composers. The section starts with the interviews.

4.4.1 Interviews with conductors

Given the candid nature of their replies, the four interviewees are here referred to as CC1 to CC4. They were given advance warning of the overall research question as to why pitch drift occurs and some gentle prompting during the interview to fulfil the aims of the meeting which were to gain opinions on what affects pitch drift, including:

- effects on pitch of pronunciation, especially vowels;
- the need for listening to oneself and others;
- environmental factors.

The interviews were seeking to confirm the results from those topics already covered by the survey and to ascertain if any new areas for investigation into why pitch drift occurs irregularly in rehearsals might be required. Each interview lasted approximately one hour. The interviews with CC1 and CC2 were face to face, those with CC3 and CC4 were via telephone. All the interviews were recorded except for CC3 which unfortunately failed due to technical problems. Fortunately, written notes were also made at each interview. CC1 and CC4 are well known choral conductors who both direct professional and amateur choirs mainly in London and its environs. CC2 is a professional musician who directs and sings with amateur choirs. CC3 is an academic who has researched extensively into choral singing and both conducts and sings with amateur choirs.

Effects on pitch of pronunciation, especially vowels

A key finding from the survey was that when choirs drift in pitch they go flat rather than sharp. This finding was fully supported by CC1 who, when asked about pitch drift in choirs replied:

> 'People sing flat! If they've been learning an instrument since they were young, or if they are a good musician, they are far less likely to sing flat because they can hear it in their mind and then they listen and correct [the pitch]. The best people at singing in tune I know are generally string players. I hear all sorts of people say, "you're singing that flat, support a little bit more", (demonstrates by singing why this doesn't work) so it's not [the] support – proved! Time of day … tiredness … vowel-sounds … no to all of these – but I've got the answer to singing in tune. (smiles broadly) If you're singing flat you have to sing a bit higher! (laughs) Say a group of sopranos are singing around D, D#, E, F area, it's terribly difficult to get inexperienced sopranos to sing in tune around there.

> (demonstrates Cleartune16 chromatic tuner app on a mobile phone) So, if they are singing a little bit under, say about a third of a semitone, I take this (mobile phone running Cleartune) to them and simply say "here you are". I don't do anything else, (demonstrates by singing flat then moving via a glissando to the correct pitch) then they get it – and they're pleased.'

However, the views of CC2 were not in total agreement with CC1 regarding the causes of pitch drift. It was CC2's opinion that:

> 'The two [issues affecting pitch drift] that are absolutely critical in my experience are listening and vowels. I think if you don't get the vowels right it will sound out of tune. This is a curious thing and I don't know the answer but if you can get agreement in a group about vowels, I'm not saying it cures the tuning, but it noticeably improves it.'

CC3 agreed with CC2 about the problems associated with singing vowels explaining that:

> 'In regard to vowels, singing an "e" (as in "See") the sound is sharper than when singing "oo" (as in "Sue") so I suggest that when singing a word with "e" then the note slightly is flattened whereas a word with "oo" should be slightly sharpened.'

With regard to vowels, CC4 described how careful pronunciation can help to maintain the correct pitch:

> 'Good training in listening and blending, and that really means vowels and diction of words more than anything else, will give the best chance of being able to tell whether [that or] other variables are moving the pitch. I think English choirs have another unique problem that choirs from other parts of the world don't have. Certainly, in London people come not just from all over the country [Great Britain] but sometimes from all over the world. Therefore, their accents and pronunciation of words are different and the vowel shapes that we make produce varying harmonics within the tone. Unless all the singers are producing full octave harmonics in their sound there will be extraneous notes creeping into the texture and extraneous sound which can give the appearance of a slightly different pitch when they [the harmonics] beat against the harmony we are singing. Not just on the vowels but also on the unified movement of diphthongs which has become quite a controversial area in the last two years and [also] how consonants are resonated. Whether the choir are supporting the letter "m" and "n" when they are putting consonants on the end of a word and are they singing the note through the hum sound or are they just letting the energy drop and effectively then giving a different note on some of their consonants. So that level of training around unifying the sound is very important. English choirs tend to sing much better blended when they're singing in Latin or in a foreign language … because they will have all learnt the same pronunciation. English choirs don't sing so well in French, which is a language

[16] Cleartune Chromatic Tuner, Bitcount Ltd., www.bitcount.com (accessed 4 September 2018)

> commonly taught in schools, and English choirs are terribly badly blended when singing in English on the whole!'

CC2 supported the thoughts of CC4 regarding choirs performing in foreign languages and agreed about diphthongs, although CC2 was less certain regarding the effects of word endings on pitch:

> 'There's an old belief that Latin gives you most vowels … I certainly find that to get my current choir to sing Latin convincingly is easier than getting them to sing English … because it's too natural. They speak it [English] all the time and it's more difficult to get them to do something artificial with their native language. Diphthongs are even worse and it's important for choirs to understand what they actually are and how they work. It was quite a few years before I did and before I started to tackle this issue, but I think individuals in a choir need to be able to understand if it's "ay-ee", (e.g. as in pain) how it breaks down and which part of the diphthong do you spend your time on. The other thing is anticipating the consonant that's coming afterwards and what happens when some people in the choir begin to change their mouth-shape into an "n" in the middle of a vowel and the colour changes, but I wouldn't say in that case the tuning changes. It all comes back to [the choir] focussing on the same thing at the same time.'

The need for listening to oneself and others

The importance of listening was emphasised by all the choral practitioners. However, CC2 thought it was not the top priority for singers whilst they were still learning the music, and indeed CC2 does not press this point with them:

> 'Listening seems to make a whole difference … but singers need reminding to listen … they don't automatically think about it. For as long as there is unfamiliarity with the notes, tuning's going to be quite far down the list of what people feel they can think about. It could be that I leave consideration of tuning until further down the line and therefore people don't think about it. While people are still finding what's the right rhythm, the right pitch, or how this new foreign language is actually pronounced, tuning is going to be on the periphery.'

CC3 stressed the importance of listening skills and also of concentration which should be maintained, if necessary, by the conductor:

> 'Excellent pitching requires excellent listening skills, which is something all singers need to develop. Concentration can lapse so it is important [for the conductor] to bring [the choir] back into focus and, if necessary, change the focus.'

In addition to listening, CC4 cites many other tasks singers undertake when performing:

> 'Listening to your neighbours, whilst following a score, whilst also following a conductor and reacting to them, and thinking about making a good sound and hearing your own sound, and analysing it, and making sure you're producing the right sound at the right moment, and remembering the notes you've already learned, and everything else that goes with it – that's a lot for the brain to be able to manage, so the brain needs a good amount of oxygen and therefore the blood needs to be flowing well, muscles need to be relaxed and tension needs to be removed. Breathing needs to be deep enough and full enough that the lungs are getting properly aerated. Being relaxed is one of the big things and sitting still for too long leads to tension and vocal fatigue. The ability of the person leading (conductor) to keep the attention of the singers I think is vitally important. If everyone is going to be focusing on this communal goal, there has to be a constant centre of focus and attention as it only takes the smallest of distractions to lose focus especially towards the end of a rehearsal.'

The need for listening is supported by CC1:

> 'The better the musician the more these (points to ears) are involved in everything they do. The more they listen to their own sound and have constant feedback … from pitch, rhythm and sound. If you're running out of breath, or your mind is on other things, or you don't care about the music, you're not doing that testing [of the sound] and the pitch goes.'

CC2 adds that key musicians with better musical skills support the choir:

> '[Good tuning] is linked to whether people can read music or not, if they are reading, they're going to get there quicker and be able to tune it. [A choir] is a kind of mixed ability context … if there are amongst the group people who have got these [sight-reading] skills, they are going to help. [On one occasion] a key bass was missing, and this made quite a big difference. People contribute different strengths, there's vocal strengths in terms of how loud people can sing and there's security, are they actually singing the right notes … it makes quite a difference if they are not there.'

The contribution 'key-singers' make to the tuning and the difference when any one of these singers are not present is stressed by CC2 as a possible reason why pitch drift may differ between rehearsals. That a difference in pitch drift can exist between rehearsals is supported by CC4 who noted that:

> 'You can take one piece of music which on one day will go a bit flat and another day won't, so you have to assume it's not the music itself that's the problem, it's how it's being brought to life that's different.'

Most choirs rehearse in their voice parts: soprano, alto, tenor and bass. However, several of the conductors spoke about the improvements to the tuning that were achieved from mixing up the parts, i.e. putting different voices next to each other. CC3 commented that:

> 'Mixed-up singing is generally better and leads to improvements when singers are back in their sections. Who the singer sits next to can make a difference to the tuning.'

This was supported by CC4 who agreed with the idea of mixing parts:

> 'Consider who singers are sitting next to, mixing them up generally sounds better and leads to improvements.'

CC1 also believes in mixing up parts:

> 'I scramble the group … and get them to sing what they were singing before, and they sing again and it's a spectacular improvement at that moment … and it's because they can hear themselves and can make the best possible sound and the intonation is better because they can hear the chord rather than their part singing the same note.'

Environmental factors

Finally, the conductors were asked about the effects of the environment, i.e. temperature, humidity and acoustic properties of the building on pitch drift. CC3 commented that

> 'High temperatures and low humidity are danger signs. It's important to keep well hydrated in these conditions. Regarding the acoustics of the building a high reverberation (wet) acoustic can be good although difficult to hear each other. A low reverberation (dry) acoustic is better for rehearsal although performing in a dead (very dry) acoustic is hard work as higher singing levels are required which needs more vocal energy.'

This was supported by CC2 who stated that:

> 'Dead space does not give feedback. But [my] previous experience singing in a big choir in a large cathedral that was so resonant (wet) that it was a nightmare. I found singing there quite alienating.'

The effects of the building's acoustic on pitch were discounted by CC1, but CC1 does express a concern regarding choral singing in very reverberant buildings, which agrees with CC2's comment:

> 'I don't think the building makes a difference. I know of a choir who think because they have a highly reverberant building they need to sing loudly. Now that sounds right doesn't it? You think because you've got a large building to fill with sound you've got to bellow, you've got to sing your head off. No! The quietist choir in the country would be heard just as well, it will be the most beautiful sound.'

To finish, CC4 recounted an experience of a performance at the viewing platform (at 244 metres high) of the *The Shard* building in London:

> 'We (the choir) had a very interesting experience with pitch wavering, it was almost like an old record that's slightly warped, across the choir and then recover. I've never heard anything like it. The only thing we could put it down too was the fact that the top of *The Shard* building has some movement in it. It was a very windy day...the building was being blown in the wind.'

There are no plans to test choirs in the way described by CC4, but it highlights how a public performance can change because of a particular circumstance, in this case movement in the building. Unexpected surroundings, external stimuli, different or missing singers, heat and humidity, etc. are all influences outside the control of the singers and conductor and yet may influence the tuning on any occasion a choir meets together and sings.

4.4.2 Correspondence with composers

To add to the experiences of choral conductors above, two of the United Kingdom's leading choral composers were approached and kindly submitted written correspondence rather than completing the questionnaire. The author is grateful for their time and agreement to allow the use of their opinions in the research. They will be referred to here as CC5 and CC6.

Regarding the direction of pitch drift CC5 has similar views to CC1:

> 'All voices are prone to singing flat, but the most important ones to cure are basses. In "normal" tonal music, the foundation of the harmony is the bass, and if

> the basses are flat nothing will sound right. If they drag the other voices down with them, that gives a horrible sinking feeling, if the other voices stay on pitch but the basses are flat, you get a different horrible effect because none of the harmonics generated by the bass note will be in tune with the upper voices. I spend a lot of time working on basses.'

CC6 also said that pitch drifting flat is far more common that drifting sharp:

> 'Going flat is much more common than going sharp and much worse to hear (or be part of). The most common causes of flat singing are: dull major thirds, especially in the tenor part; dull vowels and tiredness among singers.'

There was support from CC5 regarding vowel formation:

> 'Singing flat has several causes, but the commonest is poor vowel production. Pure, Italian *bel canto* vowels, the best sort, uncoloured by Germanic darkening, can only be produced with a fully open mouth, which people untrained in singing are unaccustomed to exercising. I always say; "open tall", not "open wide" – wide is east-west, no help, tall is north-south, which does the trick. Drop those jaws! Sing pure vowels as exercise, and don't be lazy in changing from one vowel to another – I find it useful to have choirs practise difficult passages with the consonants removed, just singing the vowels, or to sing the whole thing to "ah" or another open vowel. Poor pitching on quick notes in particular is often because vowels get turned in to what I would call non-vowels - "glo-ri-a" getting sung as "glo-rugh -a", the "rugh" being a sort of grunt.'

CC6, on the other hand, was concerned with keys, stating that:

> 'Most unaccompanied music F major or A minor will almost automatically lose pitch Give a choir a chord of F# major at the beginning of a piece in F, even without telling them, the piece will stay in tune.'

In a second letter, CC6 went on to further criticise the tenors but then agreed with the others regarding vowel production:

> 'I mentioned in the first letter major thirds not being "bright" enough. Tenors very often supply the major third in chords and are notorious for singing "under the note", as we say. However, another factor is vowel shape/colour. Bright vowels with perhaps a more smiling mouth and the vowel forward in the head, rather than dark vowels in the back of the throat, will greatly assist good intonation. An anthem we sang last week ended with the words "for thy goodness". These came out more like "far thuh good nuss" and consequently went flat. As soon as the vowels were brightened up the chords were perfectly tuned. This is one of but many examples I might give.'

CC6 also wrote about the effects of the environment but dismissed many of the possible causes mentioned in the other interviews:

> '[Pitch drifting down is caused by] stuffy, humid warm weather [also mentioned by CC3], and lack of fresh air. Going sharp almost always occurs either in very cold weather or excessive keenness and excitement. It does not appear to be affected by time of day, day of week, balance of numbers in various parts, who sits next to who, repertoire, period/style, acoustic, age group of performers, or indeed many other possible "outside issues".'

CC5 agreed over what was termed the less tangible causes of pitch drift including:

> '…fatigue or the opposite, not yet being warmed up, the weather, the acoustics of the venue, particularly insofar as it affects how well the choir members can hear each other, the language, Slavic ones seem to drive choirs flat, the nature of the choral writing, all those parallel chords in *Tavener* [John Tavener, Composer, 1944–2013] are surprisingly hard to sing in tune when they look so simple, … and some keys, in tonal music, seem to be easier to stay on pitch with than others: black-note keys are better than white-note keys, and I think the main reason for that is that, say, G flat major, if the music is fairly diatonic, avoids the tricky break in the soprano voice around E a tenth above middle C.'

CC5 also mentioned breath control and singing repeated notes as being problematic:

> 'Breath control is of course also an issue. Good singing doesn't necessarily take a huge amount of breath – good singers have long breath spans – but amateurs trying to sing the ends of phrases when they are running out of breath will probably go flat. Speaking of energy, soft singing is of course harder than loud singing, and if it becomes slack, flattening will happen. Repeated notes, especially slow ones, often lead to flattening in any voice part, but it's especially important for basses not to do it. I tell them "refresh, don't repeat" – with each repetition of the same note, think of it as a little brighter, a little higher up the sunlit path. Or, melodies that keep returning to the same note – same issue. And sustained notes mustn't sag – the thing here is to think of a long note as being on a journey, going somewhere, not stagnating in the same place. Energize it as it goes along.'

4.5 Summary

The survey, interviews and correspondence have demonstrated agreement over many possible reasons for pitch drift – both musical and physical. However, there was a wide disparity of reasons given. There was near universal agreement that pitch flattens. Over 90% of the respondents to the survey stipulated this was the case to a greater or lesser extent. The conductors and composers were in total agreement. Why this happens is arguable and outside the remit of this research. There was a majority who thought fatigue a contributory factor, but no substantiation as to why this should be the case. If this was happening with the whole choir some respondents felt the drift should be countered by action from the musical director. Recognising fatigue in individuals is more difficult and taking subsequent action not really possible without appearing to be picking on someone, naturally something that should always be avoided at any time without exception (although CC1 seemed happy to approach a whole voice part in the choir, which appears more reasonable). Breath control is seen as a problem, with the tone flattening when the breath runs out. Conductors can assist choirs with breathing by ensuring that, whilst maintaining correct phrasing, space is given for breaths to be taken by, if necessary, shortening phrases slightly. Many choral works allow for breaths, either by the provision of pauses within the bar or giving points between bars where a quick breath is recommended to ensure the phrasing remains intact and the intonation maintained. Vowel production was seen as another major cause of pitch drift. The lack of opening and correct shaping of the mouth was suggested as being responsible for flattening the pitch but the language used was also a concern, especially when singing in the choir's native language where unanimity of pronunciation is more difficult to achieve. Certain musical keys are recognised as making pitch drift more likely, indeed F major and A minor are cited as being troublesome. Moving away by a semitone often cures the problem but does not necessarily improve the overall sound as the result may not then be the one intended by the composer. Shifting the key by a semitone in order to put a particular part within the range of the singers may of course be a necessity. Environmental factors, which include the acoustic properties of the venue, the temperature and the humidity, are seen as a possible cause although results from the survey indicate that acoustic properties may not be causing problems. However, they must not be ignored.

4.6 Next steps

The most important outcome from this exercise was an overall agreement from all three sources – the questionnaire, the interviews with conductors and the correspondence with composers – that should the pitch drift when singing *a cappella* music, it is most likely to drift flat rather than sharp. Unfortunately, why pitch usually drifts down is, to date, unclear but ongoing research into possible causes due both to the music and psychoacoustical effects was discussed in the literature review of Chapter 3. It is not the intention of this research to take this matter further as it is irregular changes in pitch drift that occur from rehearsal to rehearsal which is the subject of this research.

There is overall agreement that pitch drift occurs. This is demonstrated quite clearly from the responses to the questionnaire, where pitch drift is categorised as occurring; rarely if at all, occasionally, and regularly. The reasons for pitch drift, other than that of the music, given by respondents to the survey are listed in Figure 4.25. Amongst the most popular cited which do not involve music were:

- breathing/support (10.9%)
- concentration/tired (12.7%)
- environment/venue (7.3%)
- experience/technique (8.0%)
- intervals/tuning (7.0%)
- hear/listen (10.2%)
- parts (SATB) (11.1%)
- vowel pronunciation (5.9%).

These factors, that may contribute to pitch drift, were well-supported by the interviews with the four choral conductors and correspondence from the two choral composers. Thus, they were used, along with the suggestion of CC2 that 'key singers' may make a difference, to inform the design of three experiments to be undertaken by choirs. The development of these experiments is the subject of the next chapter.

Chapter 5
Methodology

> 'Although choir singing is one of the most frequent musical activities in the world, research on the acoustics of choir singing is quite rare. This lack of research might be due to the complexity of the examination object in itself as well as the inherent demands when analysing multiple voice recordings.' (Fischinger et al., 2015)

5.1 Introduction

This chapter covers the development of the experiments designed to test different hypotheses as to why pitch drift might vary from rehearsal to rehearsal. The analysis of the outcomes from the data collected by the experiments will be covered in Chapter 6. The hypotheses are drawn from the concerns expressed by choral practitioners regarding pitch drift in *a cappella* choral singing taken from the survey, interviews and correspondence discussed in Chapter 4. Three areas were chosen for investigation as little evidence of any research studies could be found in academic literature whilst the conclusions from Chapter 4 suggests that they are of concern. They are:

- the effects of the variation of attendance on pitch drift at rehearsals;
- the environmental/acoustic influences on pitch drift;
- the ability of the singers to recognise small changes in pitch.

Research into the occurrence of pitch drift when singing unaccompanied music has mostly been undertaken in academic research establishments. In most cases the research used just one singer per part or possibly a small, select group, as demonstrated in the academic literature reviewed in Chapter 3. For this research a decision was taken from the outset that all data would be gathered from the rehearsals of amateur choirs singing in their normal rehearsal venues. Rehearsals were chosen over public performances as most amateur choirs perform infrequently in public (typically three to six performances a year). In support of this decision, the survey of choral practitioners revealed that rehearsals are usually weekly, meaning significant data could be collected over a period of about six months. However, this meant that choirs who only meet to rehearse on an irregular basis, for example a couple of rehearsals just before a public performance, had to be excluded from this research.

Nothing special would be asked of the choirs in terms of performance, indeed one of the key features of the research was that choirs should not feel that anything out of the ordinary was taking place despite their participation. There is no suggestion whatsoever that research outcomes have been affected by being undertaken in unfamiliar surroundings, such as laboratories, or by singers who have worn headsets and/or had laryngoscopes attached to them. However, there is some evidence, outlined below, that being put under investigation in research experiments can influence the behaviours of the individuals taking part.

What became known as the 'Hawthorne Effect' was first identified via a series of experiments conducted over nine years in the 1920s by the National Academy of Sciences in a Western Electric factory in Cicero, a suburb of Chicago in the USA (More or Less, 2013). The unexpected outcome was that if someone was actually concerned in some way about a group of workers, for instance through discussing their working practices or improving their environment, then the productivity of the group improved. What was more, these improvements were maintained after the investigations were concluded. However, over the years doubts have been raised as to whether experimentation does produce changes in behaviour of any group. McCambridge et al. (2014) undertook a systematic review of the literature regarding the contemporary relevance of this effect in Health Sciences. They concluded that whilst there is no single ‘Hawthorne Effect’, research participation does produce behavioural consequences although little is known of their results. Thus, given there is some uncertainty as to whether this effect is applicable or not, it was decided to try to carry out the experiments reported in this thesis in a way as to minimise any possible effects on the members of the participating choirs.

5.2 Sourcing the data

5.2.1 Introduction

In order to investigate the three areas of interest listed in Section 5.1 a decision had to be made as to what types of data were required. Uppermost was the need for regular audio recordings to be made of a number of rehearsal performances in the same venue. Just recording the whole of a rehearsal would not be very satisfactory, as to be able to compare performances from week to week it would be necessary for the same music to be sung at each rehearsal (and at the same point during the rehearsal) – which is something that couldn’t be guaranteed from a normal programme of rehearsals. It was decided therefore to use two *a cappella* songs, one especially composed for this research and sung by all the choirs, the other chosen by the choir in negotiation with the author. The recordings of these two songs at every rehearsal would then form the basis by which the relative degrees of pitch drift at and between the rehearsals could be measured. As discussed previously, the survey presented in Chapter 4 indicated that pitch drift occurs both occasionally and regularly in amateur choirs. If so, then the data from the recordings of the two songs would provide the initial evidence that, if choirs do tend to drift in pitch, it is not necessarily to the same degree at each performance.

It is unusual for any amateur choir to have a full attendance at all rehearsals over an extended period, so in order to investigate whether changes in the attendance of singers at any given rehearsal had any effect on pitch drift, a register of attendance of all singers was requested for each rehearsal. This is common practice in most choirs but was mandatory for any choir taking part in this research. This area of research was advocated by one of the choral conductors (CC2) reported in sub-Section 4.4.1. It was suggested that the presence at rehearsals of 'key-singers' can make a difference to pitch drift. The changes to pitch drift in and between different rehearsals was also supported by another of the choral conductors (CC4).

To assess whether environmental factors, such as temperature and humidity, affect pitch drift, measurements of the ambient conditions in the rehearsal venue would be made at the time of each recording. The effect of the environment on pitch was introduced in sub-Section 3.2.1 and further supported in sub-Section 4.3.4, Question 18 of the survey. Meanwhile, given the stipulation that the same venue was always to be used by each choir, it was decided that a one-off measurement of the acoustic properties of the venue with the choir in attendance would be sufficient.

Alongside the data gathering tasks described above, an experiment was implemented to establish whether the pitch discrimination abilities of the singers taking part in this research was in variance to the average of the population as a whole. Furthermore, the combined average pitch drifts of the choirs which do and do not audition singers will be tested against the results from pitch discrimination survey results for their singers. This will ascertain whether auditioned singers, who tend to be more experienced, have developed better pitch discrimination abilities compared to non-auditioned singers. The pitch discrimination tests were not mandatory as it was appreciated that not all singers might have access to an internet connected computer. Also, some singers might choose not to take part as no results would be given. This was to ensure anonymity to all participants, apart from the knowledge of their choir and in which vocal parts they sing.

5.2.2 Collecting the data

As will be seen later on in this chapter, the choirs were based around the southern and middle regions of the United Kingdom. Thus, for practical reasons, the experiments had to be run by choir members without any direct input on a regular basis from the author. Avoiding the regular involvement of someone from outside of the choir would ensure the experiments were as discreet as possible. Each choir agreed to provide, as far as they were able, the experimental data listed below from no more than 20 rehearsals using the equipment and documentation provided for the experiments.

- The date and time of the start of each audio recording.
- Digital audio recordings of the same two songs at each rehearsal sung in the same order.
- A set of environment measurements at the time of the recording.
- A register of the singers' attendance at each rehearsal at the time of the recording.
- The musical director's assessment of the performance of the choir and pitch drift at each rehearsal.
- A measurement of each singer's pitch discrimination ability (not obligatory).

The recordings should take up no more than five minutes of the choir's rehearsal time. Additional time would be needed by one choir member for logging the environmental factors and attendance data plus a few minutes of the musical director's time to complete an assessment of the rehearsal – but neither of these tasks needed the whole choir's participation. The pitch discrimination tests would take place in the singer's own time and at any convenient location where suitable computer equipment was available. The acoustic properties and dimensions of the venue would be measured by the author during the introductory meeting with the choir.

5.2.3 Recruiting choirs

This research would only be feasible if it were possible to recruit a sufficient number of choirs to ensure that significant results might be achieved. The survey of choral practitioners, discussed in Chapter 4, provided details on when and where choirs rehearse plus the average length of their rehearsals. From an analysis of the responses, requiring choirs to make recordings and collect data from up to twenty rehearsals did not seem unreasonable. This task would take the average choir, meeting on a weekly basis, around six months to complete – given that bank holidays, summer breaks and even public performances were likely to interfere with their schedule of regular rehearsals. One important proviso was that the same rehearsal room had to be used for each rehearsal in order to avoid any possible effects on pitch drift that a change in venue might cause. Two questions remained: firstly, what were the requirements for a choir to take part and secondly, how many choirs would need to be recruited for the results to be significant?

Requirements for a choir to take part

Once more, the survey of choral practitioners was able to assist in the selection of choirs by providing data on which choir types tend to perform the greater part of their repertoire *a cappella* (sub-Section 4.3.2, Q8). The survey results shown in Figure 5.1, which is a repeat of Figure 4.12, indicate that Barbershop or Sweet Adelines choruses, vocal groups and chamber choirs are most likely to sing unaccompanied music on a regular basis.

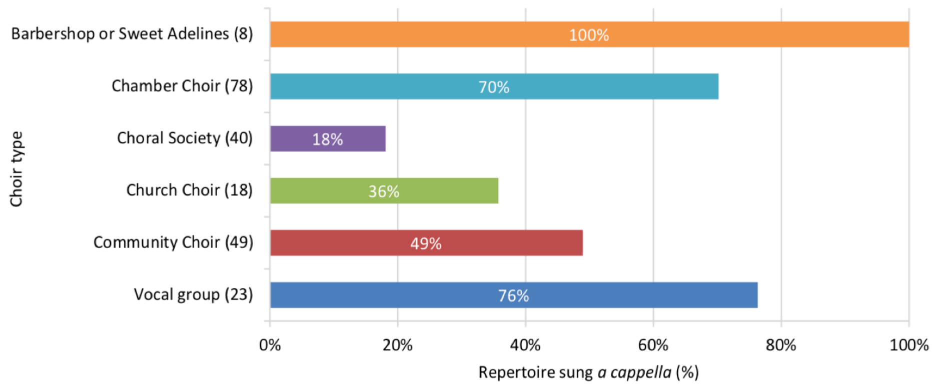


Figure 5.1 Percentage of *a cappella* music sung by different choir types (total 216) (repeat of Figure 4.12)

Whilst the size of the choir should not matter, smaller choirs such as vocal groups (typically fewer than 16 singers) were reported as having over 50% of professional or experienced singers and only rarely or occasionally experienced pitch drift (sub-Section 4.3.2, Q7). Thus, chamber choirs and Barbershop and Sweet Adelines choruses seemed the more suitable choir types to approach. It was essential to the research that choirs rehearsed on a regular basis in a single venue so choirs that only meet to rehearse just before a concert or regularly move venues (e.g. using rooms in the houses of choir members) had to be excluded. The stipulated requirements for choirs to be able to take part were that they should:

- be experienced in singing *a cappella* music (i.e. more than 50% of their repertoire);
- not have a majority of professional singers;
- rehearse regularly in a single venue;
- be able to take part over a period of at least twenty, ideally consecutive, rehearsals;
- take responsibility for running their own experiments;
- be committed to the research and its goals.

Choir numbers

How many choirs should be recruited for this research? Whilst the obvious answer might be as many as possible, there were constraints due to the equipment needed for the experiments and the timescales, which allowed approximately one year for the experiments, as shown in the research plan in Appendix 4. However, for any sets of results to have statistical significance it would be necessary to recruit at least ten choirs to run these experiments.

The recruitment process

Three recruitment methods were employed: firstly word-of-mouth, secondly a request for support through the ABCD[1] on-line magazine, and finally the research project website. The ABCD magazine produced the first choir to sign-up to this research. This was quickly followed by approaches, via spoken and email introductions, from thirteen other choirs, ten of whom eventually agreed to take part making a total of eleven choirs – one more than the minimum number. Further details of these eleven choirs are given in sub-Section 6.2.2.

5.3 Development of the experiments

5.3.1 Introduction

Of the three experiments detailed in the introduction to this chapter, the first two required the use of a suitable digital audio recorder. Measurements of the environment in the rehearsal room would involve appropriate scientific instruments, while the acoustic properties just needed a one-off recording of a suitable stimulus in the room for later analysis . The final experiment, to measure the pitch discrimination abilities of the singers, would use a survey-style online platform accessed in their own time. Suitable documentation was necessary to support all the experiments.

5.3.2 Making the digital audio recordings

Sub-Section 5.2.3 reported that eleven choirs were recruited to take part in the experiments. Given that audio recordings from twenty rehearsals were needed and that the choirs only rehearsed once a week, the practical solution, bearing in mind the timescales for the research, was to run the experiments concurrently. Equipment for six experiment kits was eventually sourced enabling all of the choirs to take part in two six-monthly periods in the year allocated to this aspect of the research.

[1] Association of British Choral Directors, www.abcd.org.uk (accessed 31 October 2018)

Requirements of a digital audio recorder

Making digital audio recordings of the choirs' rehearsals was key to the research. Any recorder chosen needed to be simple to use, offer good quality sound, be reliable and within budget. An investigation of possible devices established that although many excellent digital audio recorders were available their costs were well in excess of the allocated budget. Closer investigation revealed that these digital audio recorders could be quite complicated to use, due largely to offering many options and facilities designed for professional and advanced amateur users. The experiments, however, required the involvement of a willing, but not necessarily technical, choir member, so equipment that was straightforward to use was essential. For example, any problems with a recording would mean taking time out of an additional rehearsal which would be unpopular both with the musical director and the singers. (How many recordings have been lost because something was not setup correctly on the audio recorder when the record button was pressed?)

If digital audio recorders were ruled out by complications and costs, could a digital voice recorder be used instead? Voice recorders offer fewer facilities; they mostly only record a single channel (i.e. monaural sound) and may only produce compressed (MP3) sound files, but neither of these restrictions are drawbacks to measuring pitch, as discussed later on in this sub-section. However, the frequency response was an important consideration as it might affect the measurement of pitch. The human singing voice covers a range of musical notes from E_2 (110 Hz) to above C_6 (1760 Hz) in some cases. Thus, any digital audio recorder should be able to record sounds from under 100 Hz to above 10,000 Hz to ensure the main associated harmonics are captured.

Selecting a suitable digital audio recorder

Three digital voice recorders were obtained from different manufacturers for evaluation. It quickly became apparent that the two less expensive models were unsuitable because the recording level was fixed. As supplied, both recorders were far too sensitive for recording the high sound pressure levels generated by choirs (sub-Section 2.3.3). This meant the recorded sound could be distorted leading to unwanted harmonics that could complicate the pitch analysis of the recordings. The high sensitivity recording level was quite understandable as these recorders were designed to record individuals speaking either in a lecture hall or meeting room as well as dictation. Certainly not for recording upwards of thirty people singing fortissimo! As there was no obvious way to reduce the recording sensitivity on either of these two models, further tests were abandoned. The third model, a Sony ICD-PX333[2] recorder shown in Figure 5.2(a), was well built with a large LCD display (of the other two models tested, one had a very small LCD display and the other just had a red LED recording indicator). It was the most expensive recorder of the three but, coming from a recognised manufacturer of quality consumer electronics, would convey a good impression to the users. This recorder is fitted with a top mounted internal electret microphone (Figure 5.2(b)). When tested it was found capable of capturing sounds without distortion from the high sound pressure levels produced by choirs. This was because, unlike the other recorders considered, this model has three record level settings that ensured distortion-free high quality recordings could be captured. Furthermore, should the recording level be pre-set to the least sensitive position the internal signal-to-noise ratio was so high that if post-recording amplification of low-level audio signals was necessary any internal noise remained at acceptably low levels.

The frequency range of this recorder in the ‘super high quality’ (SHQ) recording mode (MP3 192 kbps) was quoted as being 75Hz to 20,000 Hz (Sony Corporation, 2013) making it very suitable for capturing choral singing. Although recordings were made with just a single microphone, the recorder created stereo audio files in the SHQ mode (with identical contents in each channel) allowing playback on any MP3 player or computer application.

[2] www.sony.co.uk/electronics/voice-recorders/icd-px333 (accessed 15 October 2018)

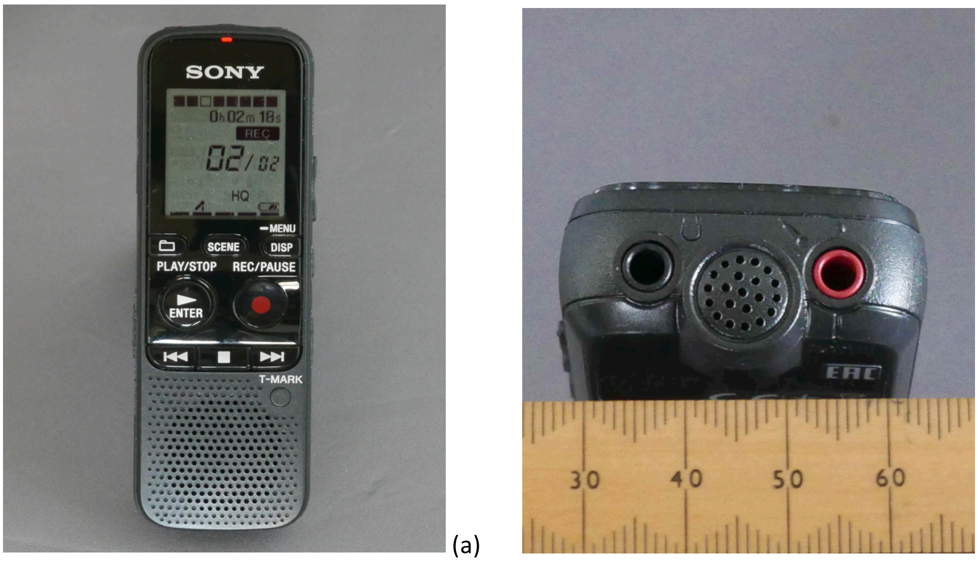


Figure 5.2 (a) Sony ICD-PX333 digital audio recorder; (b) the width of the recorder against a mm scale and showing the microphone grill

At 4 GB, the internal memory store had the smallest capacity of the three recorders tested. However, an external *Secure Digital micro storage card* (SD micro-card) is supported, although this was not essential as the internal storage would be more than sufficient for all of the proposed recordings (approximately 100 minutes). Five minutes of recording time in each of 20 rehearsals at a data rate of 192 kbps requires only 144 MB of memory. However, fitting inexpensive external 8 GB SD micro-cards in the recorders to store the recordings meant each card could be retained as a security back-up for each choir. Furthermore, the recorder's internal memory could be employed if the external memory card failed for any reason.

From the point of view of the choirs, the question was just how easy might this audio recorder be to use? To make a recording the user toggles the side-mounted on/off switch to power up the recorder. Once the home screen is displayed (Figure 5.2(a)) the record/pause button (labelled with a red spot) is pressed once and a recording starts immediately. A moving bar at the top of the display indicates when a recording is in progress and the display showing the time remaining on the memory card decrements. The recording is halted by pressing the stop button (labelled with a white square). Finally, the on/off slide-switch is toggled again, this time to turn the power off.

Sound files are automatically generated, numbered and date-stamped each time a new recording is made. Up to 99 sound files in each one of four folders can be stored. These folders can be accessed by a computer via a supplied USB 2.0 cable – the recorder appearing as an external memory device – although users were not required to back-up the recordings on their own computers unless they chose to do so. A power level indicator shows the state of the battery and additional cells were provided in the experiment kit. The procedures for changing the battery and resetting the date and time were described in the *Experiment Handbook*, reproduced in Appendix 5. This booklet also describes the experiments and operation of the equipment along with contact details in case of problems. In addition, the manufacturer's operating guide was included in the kit.

Testing the digital audio recorder

To ensure the Sony ICD-PX333 recorder created sound files from which accurate pitch measurements could be taken, audio tests were recorded using the 192 kbps MP3 file format. A comparison was then made against the well-regarded *ZOOM Handy Recorder H2*©[3] ZOOM Corporation, Japan. This digital audio recorder was set to the more usual 16-bit uncompressed file format. Both recorders used a standard 44.1 kHz sampling rate. An audio test waveform of a C major chord, comprising four pure tones of equal tempered pitches C_4, E_4, G_4 and C_5, was created on and played by *Audition CS6*, Adobe Inc., running on an *Apple MacBook Pro*. The analogue audio output from the *MacBook Pro* was fed through a *Quad* 34 preamp and 306 power amplifier to a pair of monitor loudspeakers built to the *BBC LS3/5A* specification. Simultaneous recordings of this chord were made on both recorders. The resulting sound files were analysed without further processing using *Melodyne Studio* from

[3] www.zoom-uk.com/products/field-video-recording/field-recording/zoom-h2n-handy-recorder (accessed 15 October 2018)

Celemony Software GmbH, which was selected to make quantitative analyses of the recordings of the choirs and is described fully in Chapter 6. The results of the tests on the two recorders are listed in Table 5.1.

Table 5.1 Comparison of digital audio recorders using *Melodyne*

Note		Zoom H2 (wav)		Sony ICD-PX333 (mp3)	
Value	**Frequency (Hz)**	**Note value**	**Frequency (Hz)**	**Note value**	**Frequency (Hz)**
C_4	261.63	C_4 +0 cents	261.6	C_4 +0 cents	261.6
E_4	329.63	E_4 +0 cents	329.6	E_4 +0 cents	329.6
G_4	392.00	G_4 +0 cents	392.0	G_4 +0 cents	392.0
C_5	523.25	C_5 +0 cents	523.3	C_5 +0 cents	523.2

The results from the two recorders compare well apart from a minor difference in the frequency measurement of note C_5 of an insignificant 0.1 Hz, but making no difference to the value of the pitch (C_5 +0 cents) which, as will be explained in sub-Section 6.4.3, is how pitch drift will be quantified in this thesis.

Having confirmed the Sony ICD-PX333 digital audio recorder would be suitable, the decision was taken to purchase an additional five recorders along with a number of 8 GB micro SD cards for use with the choirs.

5.3.3 Environmental factors

Results from the survey of choral practitioners suggested that environmental factors within the rehearsal venue might affect the pitch drift. The environmental factors include:

- temperature
- humidity
- atmospheric pressure
- light levels
- background noise.

Note that it was subsequently found light levels and background noise did not appear to change at the rehearsal venues and so these two factors were not used in the analyses of the effects of environment factors on pitch drift.

Making measurements

Automatic data loggers would have been the ideal way to collect the environmental data but their use in this research was not possible as suitable devices were found to be prohibitively expensive. Furthermore, such devices would have required the use of a computer to store the data following each rehearsal, which might not be possible as computer ownership by choir members could not be taken for granted. It would also place an unnecessary responsibility onto the person storing the data. On the other hand, manual measurement simply required someone to take the appropriate readings from the environment meter and complete a prepared log sheet at each rehearsal. This was thought to be a reasonable ask of the choir member who was making the audio recordings as the environmental measurements were required at the time of the recordings.

Selecting a suitable environment meter

Research into the availability of suitable environmental measuring instruments revealed several distributors offering suitable devices that allowed four of the five environmental factors listed above to be measured (temperature, humidity, light and sound pressure levels). The device selected, a *Precision Gold 4–in–1 Environment Meter*[4] is shown in Figure 5.3 and was available within the budget. The ranges, accuracy and resolution of this meter were considered adequate for the requirements of the research and are listed in Appendix 6.

[4] www.test-meter.co.uk/4-in-1-environmental-test-meter/ (accessed 15 October 2018)

Figure 5.3 Precision Gold 4–in–1 environment meter with temperature and humidity sensors (left) and light level sensor (right), which is not normally plugged-in as shown here. The microphone for sound pressure level measurement at the top is covered by a wind shield

This instrument has a large 3.5-digit LCD display. A slide switch selects the required measurement and buttons operate power on/off (with auto power off after 10 minutes of inactivity), range selection, max-hold and data-hold. Operating instructions were included in the *Experimental Handbook* (Appendix 5) and an environmental measurements log sheet was provided for the choir member to complete at the time of each recording (Appendix 7).

Initially, readings of four environmental factors were logged. When it became apparent from feedback by the first cohort of choirs that light levels and background noise did not vary they were stopped for these choirs and all subsequent choirs leaving just temperature and humidity to be measured. However, taking readings of atmospheric pressure proved unexpectedly problematic.

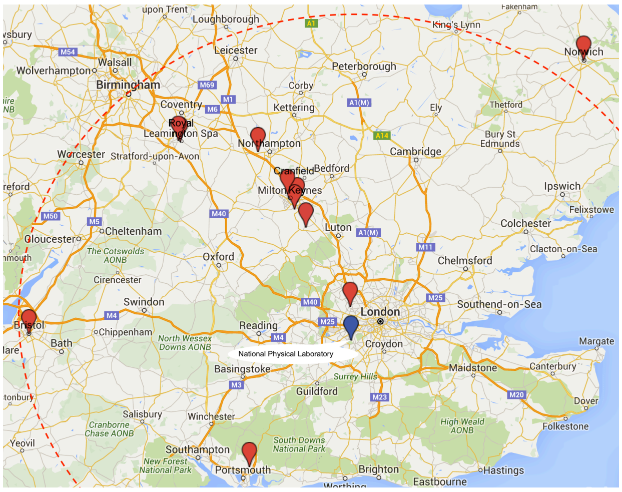
Measuring atmospheric pressure

Taking readings of the atmospheric (barometric) pressure presented a challenge. No suitable barometric data logger or mechanical barometer could be sourced within the budget. After researching alternative ways of measuring atmospheric pressure, readings from the National Physical Laboratory[5] were used along with those from airports nearest to the choirs. The NPL is situated at Teddington, south-west of London as shown in blue on the map in Figure 5.4, and fortuitously happens to be reasonably centrally located and within a

[5] resource.npl.co.uk/pressure/pressure.html (accessed 22 December 2018)

radius of approximately a one-hundred miles of all the choirs taking part (shown in red on the map). The NPL logs barometric measurements at five minute intervals and publishes daily and weekly barograph charts on their website. Furthermore, up to the end of 2017 (when they withdrew the service), the NPL allowed free access to their historical barometric data for every year dating back to 1998. Thus, retrospective barometric data could be found for the time of each rehearsal (in years 2015/6) and added to each choir's environmental data log when it was returned. However, because there could be possible discrepancies in accepting NPL barometric data due to its distance from some choirs, barometric readings from the from local airports based in Bristol, Coventry, Cranfield, Norwich and Southampton were also used (see map). Comparing the two readings ensured that the most accurate values of atmospheric pressure at the time and place of rehearsals could be achieved.

Figure 5.4 Locations of the National Physical Laboratory south-west of London (in blue) and choirs taking part in the experiments (in red). The dashed-red circle shows all choirs to be within approximately a 100-mile radius of the NPL in Teddington



5.3.4 Selecting the music

Choirs were asked to sing two pieces of *a cappella* music at each rehearsal. The first song, called *Test Piece*, was sung by all choirs. A copy of the score may be found in Appendix 8. This four-part *a cappella* work was specially composed for this research by Dr Dennis Pim of the Open University. It was planned to use *Heraclitus* (C. V. Stanford, 1852–1924) as the second piece, this also being an unaccompanied part-song for four voice parts. Unfortunately, not all the choirs considered this piece to be an appropriate song for them to perform; either it was not in their repertoire (and they did not want to learn another new work as well as *Test Piece*), or it was thought to be of an inappropriate genre and not available in arrangements for Barbershop/Sweet Adelines choruses. Following discussions, it was agreed that choirs could either choose a song from their repertoire or one being learned for a forthcoming concert. The only provisos were that the chosen song had to be performed *a cappella* and it should be no more than four minutes in length. This means the second piece performed by the choirs (including the choirs who chose to sing *Heraclitus*) will be referred to simply as the 'chosen song' in this thesis. All the songs chosen are listed in Appendix 9.

Applying predictive analysis to the music

A fragment of Pim's *Test Piece* is shown in Figure 5.5. It is a wordless, short and straightforward homophonic four-part song that doesn't modulate much from the home key, so minimising the chance that the music itself might cause a drift in pitch. Changes in sung vowel sounds ('do', 'la', and 'ti'), cited as a cause of pitch drift in both the literature review and survey of choral practitioners, were included in *Test Piece* to allow this suggested cause of pitch drift to be investigated from the recordings. Although outside the scope of this research, the use of vowels in *Test Piece* may be of help to others investigating this field.

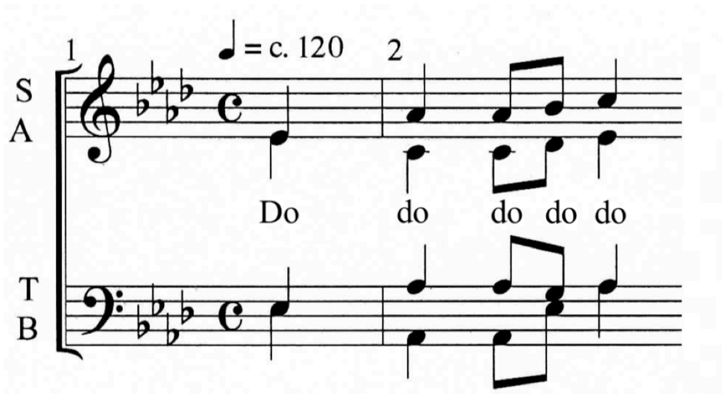


Figure 5.5 Fragment of *Test Piece*© showing bars 1 and 2 (with permission)

Test Piece was examined using Howard's latest predictive methodology (unpublished at the time of writing). Introduced in Section 3.5.1, this procedure predicts the likelihood of the pitch drifting due to the composition of the music. The differences in pitch are calculated assuming singers tune from the tonic of the chord, in which ever vocal part it occurs, using just intonation (i.e. in simple ratios) rather than in equal temperament tuning (i.e. in equally spaced semitones). The difference between the two tuning methods forecasts that over the entire song the pitch may drift up, drift down or stay neutral. Figure 5.6 demonstrates the predicted pitch drift of Pim's *Test Piece*. It shows that whilst individual chords within the piece may be expected to sharpen or flatten, the last chord is just five cents sharp compared with the first chord. Thus, *Test Piece* is predicted to stay neutral – which was Dr Pim's intention when composing the song and, according to Professor Howard, eliminates the possibility of pitch drift occurring during a performance of this piece being due to the harmonic structure of the music.

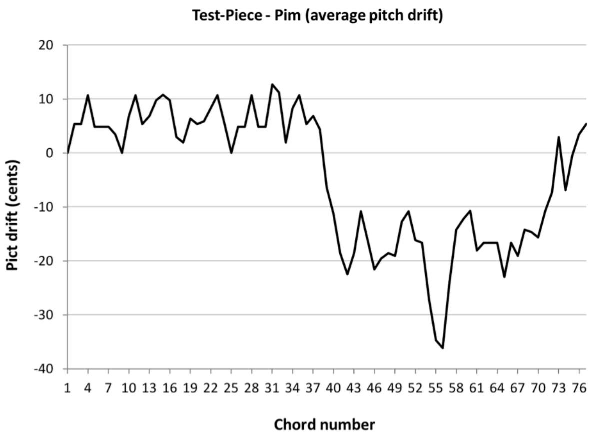


Figure 5.6 Howard's predicted pitch drift for Pim's *Test Piece*

As mentioned above, Stanford's *Heraclitus* was originally chosen as the second song because the overall pitch drift prediction for this work is only ten cents flat, as shown in Figure 5.7, so this piece is also predicted to remain neutral. However, it does have a wider variation in its predicted drift than *Test Piece*, drifting down by 100 cents at chord 54, as opposed to *Test Piece* which in the worst case drifts down by 35 cents at chord 56.

Interestingly, on average *Heraclitus* took the fours choirs who chose this piece over a minute longer to sing than *Test Piece*. This difference in duration between the chosen songs selected by the choirs and *Test Piece* will be commented on in Chapter 7.

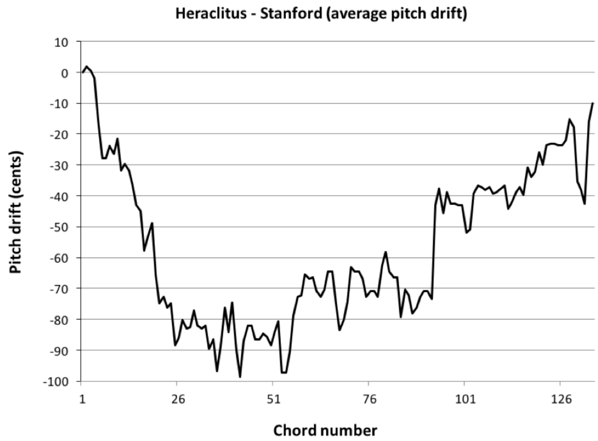


Figure 5.7 Howard's predicted pitch drift for Stanford's *Heraclitus*

Locus iste (Anton Bruckner, 1824–1896) was selected by two of the choirs as their chosen song. Here the predicted pitch drops by nearly a tone (200 cents) by the end of the piece (48 Bars), as may be seen from Figure 5.8. Terasawa reported that a particular choir always dropped a semitone each time Bruckner's *Os Justi* was sung (Section 3.2.3). Although his research predated all of Howard's work in this field, Terasawa's results appear to support those of Howard – that the composition is likely to be one possible cause of pitch drift.

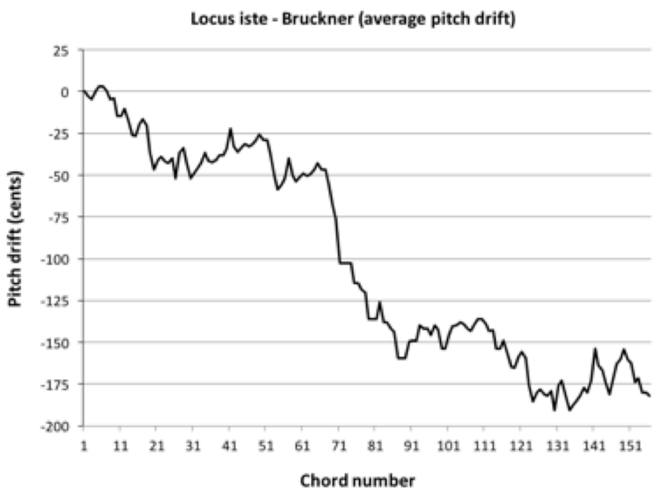


Figure 5.8 Howard's predicted pitch drift for Bruckner's *Locus iste*

Unfortunately, none of the other chosen songs used by choirs in this research have to date been tested for predicted pitch drift.

Predictive analysis of pitch drift offers an important insight into why certain *a cappella* pieces tend to drift in pitch. However, it does not help explain why the pitch drift varies at different rehearsals or indeed for example why, despite being predicted to drop by nearly a whole tone (200 cents), *Locus iste* may well stay reasonably in tune.

5.3.5 Determining the acoustic properties of rehearsal rooms

Choirs usually rehearse indoors even if they occasionally give performances in the open air. In the latter case, singers will certainly notice a difference to their sound – for example, listening to one another is far more problematic as there is no acoustic feedback that comes from singing in an enclosed space. Whilst the acoustic properties of rehearsal venues will not change unduly over time, it was considered worthwhile to determine whether any correlation exists between the acoustic properties of different venues and the pitch drift of the choirs who sing there. Since every choir was to be visited by the author to introduce the research, etc., an opportunity was taken to measure the acoustic properties of its venue with the choir members present. It was of course necessary to make the acoustic measurements with the singers present and in their usual rehearsal positions as the presence of a number of people, especially in a small room, can significantly affect its acoustic properties.

Measuring acoustic properties

Measuring the acoustic properties of a room has been made very straightforward by the use of specialist computer applications that deliver results in the standard terms laid out in the set of International Organization for Standardization's documents, ISO 3382, *Acoustics – Measurement of room acoustic parameters – Parts 1 and 2*, (ISO, 2015) and (ISO, 2016) respectively. Computer applications use an audio recording of a stimulus in the room to process the results. This stimulus should cover as many frequencies in the audible range as possible, since any room will react to certain frequencies more than others. Typically, a starting pistol firing blank cartridges is used to provide a suitable stimulus, with the impulse-like burst of sound providing a broad audio band excitation in the room. However, it is not always practical to carry out measurements in this way, particularly when people are to be present. To overcome this problem, a chirp (an audio sweep signal from 20 Hz to 20 kHz) generated by the acoustic computer application was planned to be used, but setting up and taking down all the necessary equipment, including a stand-mounted dodecahedron speaker, constructed by the author and shown in Figure 5.9, was thought to be too intrusive during a choir rehearsal. Unfortunately, early access to rehearsal venues to setup the equipment before a choir's arrival was not usually possible – hence the need for an alternative method. Tests in an anechoic chamber at the Open University's campus in Milton Keynes, demonstrated that a balloon burst was just as effective in stimulating an enclosed space – and much simpler to deploy. Before making any recordings of balloon bursts at a choir's rehearsal any singer who found the sound unpleasant was invited to leave the room.

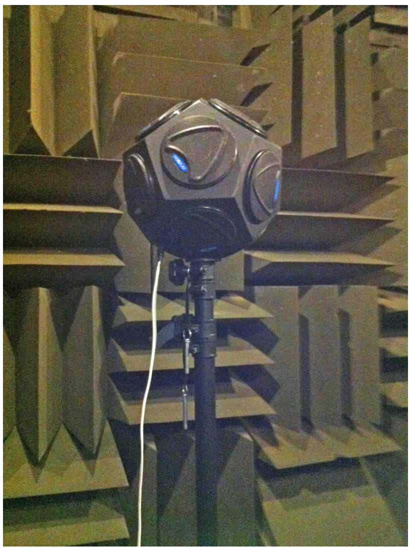


Figure 5.9 Dodecahedron speaker under test in the Open University's anechoic chamber. The design was adapted by the author from a web article at: www.prosoundtraining.com/ 2010/03/17/build-your-own-dodecahedron-loudspeaker/ (accessed 18 June 2019)

A *Tascam™ DR-44WL*[6] digital audio recorder shown in Figure 5.10 was used for the impulse recordings. Uncompressed 16-bit wave sound files were made with a 48 kHz sampling rate, as required by the acoustic analysis application discussed below. No automatic level control or audio compression was applied.

Figure 5.10 The measurement microphone and digital audio recorder

This recorder has a useful feature which takes the same input source and creates two sound files using different record level settings. The first file is created using the pre-determined level set by the user and the second level is set to 12 dB below the first. This means that should the first file distort due to the pre-set level being too high, which may happen with an uncontrolled sound such as bursting balloons, the second file is likely to be undistorted. Balloons are not entirely predictable and can produce different sound levels despite being inflated to the same diameter.

The measurement microphone used was a *Behringer®*[7] *ECM8000* shown in Figure 5.10. When positioned vertically, this type of microphone has an omnidirectional characteristic,

[6] tascam.com/us/product/dr-44wl/top (accessed 15 October 2018)
[7] www.musictribe.com/Categories/Behringer/Microphones/Condenser/ECM8000/p/P0118 (accessed 14 August 2105)

as shown in Figure 5.11, with a frequency response within ±2 dB over the audio range of 20 Hz to 20,000Hz. The recorder supplied the 48 V phantom power for this microphone.

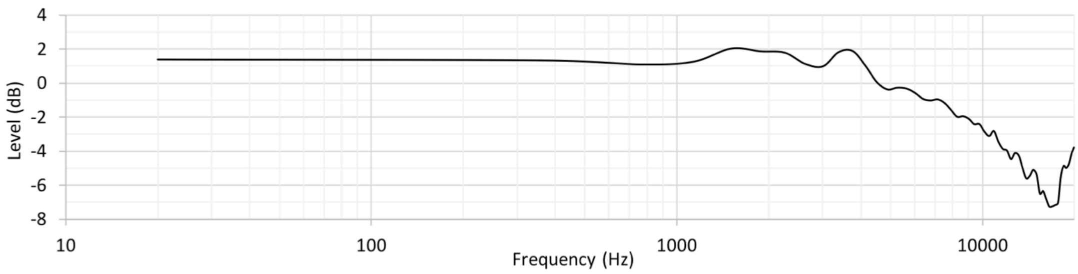


Figure 5.11 Measured frequency response for the *Behringer® ECM8000* measurement microphone. This was obtained by comparison against a Brüel & Kjær ½" free field microphone cartridge type 4966 with a preamp type 2699 and type 5935 power supply in the anechoic chamber at the Open University campus. The source was a Brüel & Kjær *OmniSource* type 4295 with a 'chirp' from 20–20,000 Hz. The *ECM8000* frequency response is within ±2 dB between 60 Hz and 8000 Hz, the accepted range of the human voice

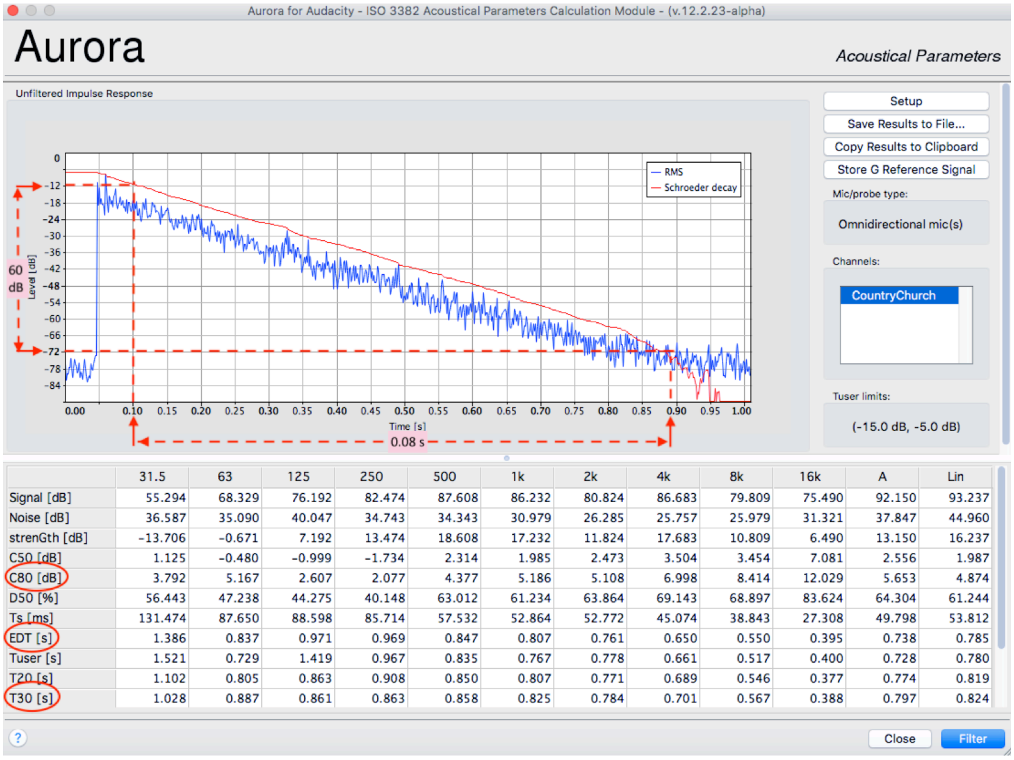
Analysing the impulse recordings

To determine the acoustic properties of the choirs' venues, the *Aurora*[8] suite of add-in modules for computer-based digital audio editors was used. *Aurora* provides all the processes necessary for making acoustic measurements from the generation of a chirp stimulus through to the calculation of the acoustical parameters to the ISO 3382 specification. Development of *Aurora* was undertaken by Farina (2000) who created a series of 16 modules, initially for use with *CoolEdit*, Syntrillium Software Corporation, and later with *Audition* v3*.* Campanini and Farina (2009) also developed six of the modules for use with *Audacity* v2.0[9] which is available for many computer platforms. Recent updates to both *Audition* and *Audacity* means *Aurora* modules are no longer supported. Fortunately, *Audacity* v2.0 still runs on current *Windows, OS X* and *Linux* platforms making *Aurora* suitable for use in this research.

The sound files of bursting balloons, recorded at each choir's rehearsal venue, provide the source for determining the acoustic parameters discussed in sub-Section 2.3.7. As an

[8] Aurora: pcfarina.eng.unipr.it/Aurora_XP/index.htm (accessed 20 November 2017)
[9] www.audacityteam.org (accessed 20 November 2017)

example, the results from *Aurora* using the recording of a balloon bursting in a small English country church are shown in Figure 5.12.



	31.5	63	125	250	500	1k	2k	4k	8k	16k	A	Lin
Signal [dB]	55.294	68.329	76.192	82.474	87.608	86.232	80.824	86.683	79.809	75.490	92.150	93.237
Noise [dB]	36.587	35.090	40.047	34.743	34.343	30.979	26.285	25.757	25.979	31.321	37.847	44.960
strenGth [dB]	-13.706	-0.671	7.192	13.474	18.608	17.232	11.824	17.683	10.809	6.490	13.150	16.237
C50 [dB]	1.125	-0.480	-0.999	-1.734	2.314	1.985	2.473	3.504	3.454	7.081	2.556	1.987
C80 [dB]	3.792	5.167	2.607	2.077	4.377	5.186	5.108	6.998	8.414	12.029	5.653	4.874
D50 [%]	56.443	47.238	44.275	40.148	63.012	61.234	63.864	69.143	68.897	83.624	64.304	61.244
Ts [ms]	131.474	87.650	88.598	85.714	57.532	52.864	52.772	45.074	38.843	27.308	49.798	53.812
EDT [s]	1.386	0.837	0.971	0.969	0.847	0.807	0.761	0.650	0.550	0.395	0.738	0.785
Tuser [s]	1.521	0.729	1.419	0.967	0.835	0.767	0.778	0.661	0.517	0.400	0.728	0.780
T20 [s]	1.102	0.805	0.863	0.908	0.850	0.807	0.771	0.689	0.546	0.377	0.774	0.819
T30 [s]	1.028	0.887	0.861	0.863	0.858	0.825	0.784	0.701	0.567	0.388	0.797	0.824

Figure 5.12 Screenshot of the ISO 3382 Acoustic Parameters calculator

The graph in the screenshot indicates the room response to the impulse sound. The Schroeder decay (thin diagonal red line) has been calculated and added to the graph to allow an estimation of the reverberation time RT_{60}. Taking the measurement between –12 and –72 dB (i.e. decay of 60 dB) gives a time span between 0.1 s and ~0.9 s resulting in a decay time of ~0.8 s. The table below the graph gives a set of acoustic parameters (including T_{30}, C_{80} and EDT, ringed in red) for the church to the ISO 3382 standard in ten octave bands, from 31.5 Hz to 16 kHz, plus the 'A' weighted values (i.e. approximated to the response of the human ear) and the linear values (i.e. no weighting applied). These results may be saved and copied to an *Excel* worksheet for further analysis.

The dimensions of the rehearsal room were determined from architect's plans when available but measurements were also taken using an ultrasonic distance meter (*Metek*

MDM-201A[10]). These dimensions may be used to estimate the reverberation time (RT_{60}) of the room using Sabine's reverberation formula (Howard and Angus, 2006, p. 285) should the impulse recording prove unsuitable for any reason. Sabine's formula also requires details of the construction and furnishing in the rooms. These details were not noted at the time of the impulse recording, but the choirs would always have been able to provide these details if needed. In the end this was not necessary as all the recordings made at the rehearsal venues provided satisfactory results.

5.3.6 The musical director's questionnaire

A report on the performance of the choir at each rehearsal was requested from the musical directors. They were expected to complete a brief paper-based questionnaire at the end of each rehearsal (Appendix 10). The questionnaire was in two parts, the first asked for ratings of the performance of the songs, the second asked for a rating of the pitch drift. The ratings were based on a scale; from 'A' (excellent) to 'E' (poor), and additional comments to underpin the ratings were requested. The musical directors were also asked to report if any 'key-singers' had not attended the rehearsal (without naming any particular individual).

This qualitative data was to be used alongside the quantitative pitch measurements to give a fair pitch drift rating for each song at each rehearsal. The procedure used to determine pitch drift ratings is described in detail in Section 6.5.

5.3.7 Pitch discrimination tests

A series of tests were designed to determine the pitch discrimination abilities of the singers from the choirs that took part in this research. This relates to the third of the three areas of concern mentioned in the introduction to this chapter.

[10] www.metek.com.hk/product.asp?nclassid=13 (accessed 15 October 2108)

The design of the pitch discrimination tests

Our ability to discriminate between different pitches was discussed in sub-Section 3.4.1. Apart from those individuals with absolute pitch (sub-Section 3.4.3), the average person in the general population is able to discriminate between two tones based around A_4 (440 Hz) when they differ by ±12 cents (approximately ±3 Hz). There is evidence from a recent paper (Smith et al., 2017) which suggests that better performance in pitch discrimination may be associated with formal music training (especially before the age of six) plus (rather surprisingly) having English as a native language. Might it be that choral singers have a better ability to discriminate small pitch differences, particularly if their choir has a policy of auditioning prospective singers? If this is the case then the pitch discrimination of individual singers could have a bearing on any pitch drift, hence the need to undertake an assessment of their pitch discrimination abilities.

In a series of tests delivered via an online survey platform, singers were asked to discriminate between pairs of pure tones by deciding whether the two tones sounded the same or different. Taking part was voluntary and no results were made available to the participants as the results were anonymised. Furthermore, giving out individual results would allow singers to compare results – which might upset or concern those who didn't do too well. Each member of the choir received a written invitation to take part which included a simplified internet address (TinyURL[11]) for the link to the bespoke pitch discrimination tests website for their choir and a password to access the tests. It was appreciated that not all the singers would be able to take part; however, it was hoped that sufficient singers would participate to give significance to the results. The importance of this exercise was stressed to musical directors, who were asked to encourage their singers to take part.

[11] tinyurl.com (accessed 1 August 2015)

Generating pure tones

To ensure the pure tones were as accurate as possible they were generated as uncompressed 16-bit wave sound files at 44.1 kHz sampling rate using the mathematical computing software *Matlab®* from The Mathworks Inc., USA. The program code (Appendix 11) used similar frequencies to Seashore (1938, p. 56), listed in Table 5.2. The tone duration was specified as two seconds and an appropriate filename with .wav extension was also entered into the *Matlab* code. Seashore's frequencies used for his tones were adjusted to the nearest cent, as this research uses note values and offsets in cents for specifying pitch. An *Excel* worksheet was used to generate a range of equal temperament frequencies, based on A_4 = 440 Hz, shown in Table 5.2.

Table 5.2 Tone frequencies used for the pitch discrimination tests (a negative cent value implies a flattened tone)

No.	Frequency (Hz)	Variation from A_4 reference (cents)
1	427.968177	–48
2	431.941776	–32
3	434.946169	–20
4	435.952270	–16
5	436.960698	–12
6	437.971459	–8
7	438.984558	–4
8	439.491986	–2
9	439.745919	–1
10	**440.000000**	**0**

No.	Frequency (Hz)	Variation from A_4 reference (cents)
11	440.254228	1
12	440.508602	2
13	441.017792	4
14	442.037937	8
15	443.060442	12
16	444.085313	16
17	445.112554	20
18	448.298556	32
19	452.370084	48

The choice of the tone differences and the number of tone pairs ensured that any candidate with average pitch discrimination taking the tests should be able to discriminate between more than half of them. This was seen as important to ensure candidates did not feel discouraged if they were struggling to discriminate between the tones in the pairs. By way of reassurance, candidates were advised in the instructions not to be overly concerned if several pairs sounded the same – for indeed there were four pairs of tones that were equal. These four equal tone pairs were necessary to try to detect any results which might be due to guesswork as, for instance, if all four pairs were reported as being different.

Frequency values to six decimal places were used to generate each tone simply because the *Matlab* routine could accept these values which were calculated in an *Excel* worksheet using Equation 2.5 from sub-Section 2.3.4. Using the frequencies from Table 5.2, twenty-two stereo sound files were generated, eighteen with differing pairs of tones and four with both tones set to 440 Hz. Stereo sound is a common format for sound files and ensured compatibility with the widest range of web-browsers and media-player plug-ins.

Following Seashore's practice, the first tone was always set to 440 Hz followed by one of the tones from Table 5.2. A period of 0.2 seconds of silence was added at the beginning, between, and to the end of the tone pairs. Cosine S-curve fading over a period of 0.2 seconds was applied at the beginning and end of each tone and the amplitude normalized to –3 dB. The waveforms shown in Figures 5.13 and 5.14 are taken from one of the sound files used in the tests. Each of the sound files was saved using a random code as the filename to ensure that if any file was downloaded accidently no indication as to the frequencies of the two tones could be inferred. A 'key-file' held the master list of the filenames along with the offset in cents of each second tone.

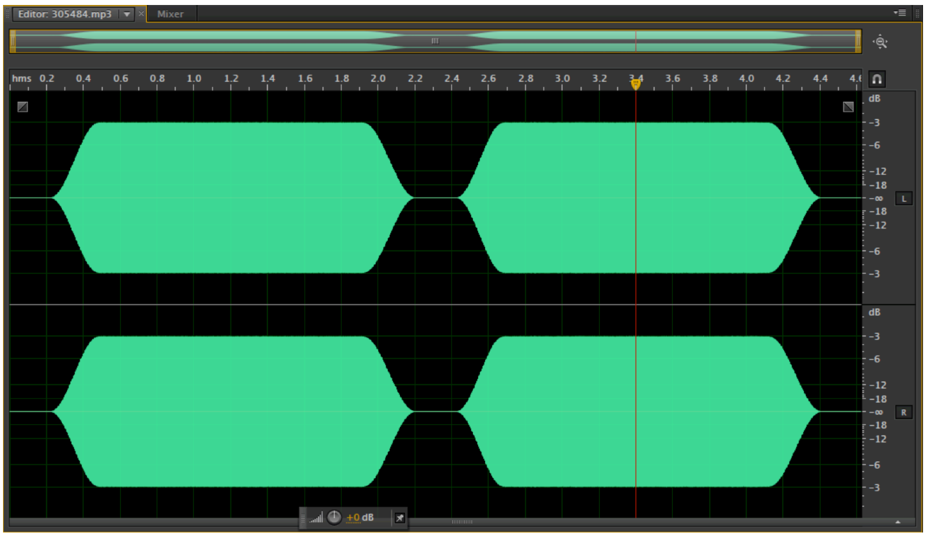


Figure 5.13 Example waveform of a stereo sound file with +20 cents difference used in the pitch discrimination tests using *Audition*

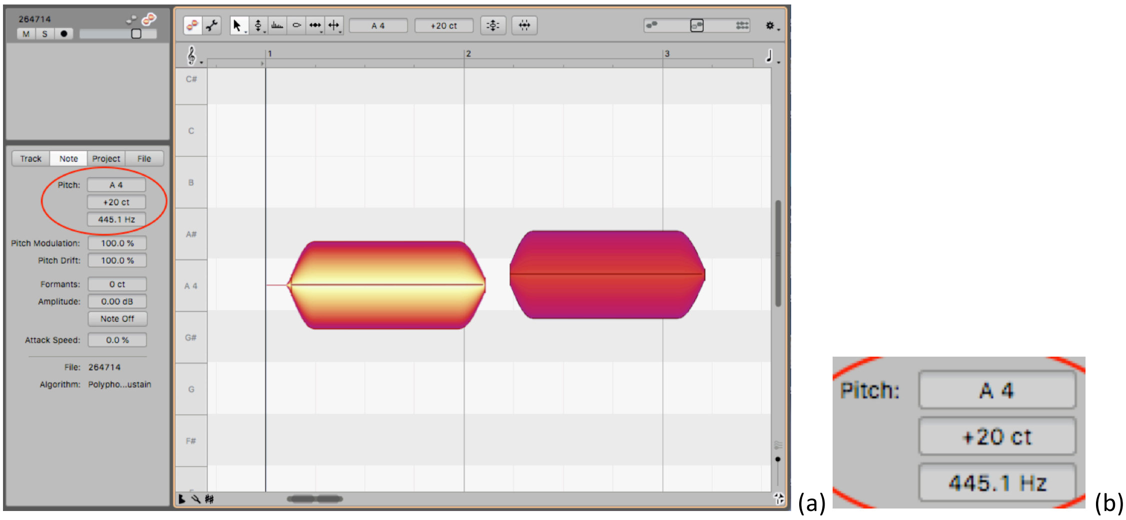


Figure 5.14 (a) *Melodyne*'s note analysis of a single channel from the waveform in Figure 5.13 showing the second tone (highlighted in red) to be higher in pitch than the first tone (set to A_4) by 20 cents (ringed); (b) detail of the results for the selected tone

Designing the platform for the tests

The pitch discrimination tests used a survey platform from *Surveygizmo*®[12] Boulder, Colorado, USA. This online platform allowed sound files to be embedded within the questions whereas, at the time of building this survey (2015), the platform used for the previous survey in Chapter 4 did not support this feature. Each choir had a bespoke survey-file with the choir's name, an identical set of pitch discrimination tests, a list of appropriate voice parts and password protection. Participants were allowed to access the set of tests more than once in case they experienced problems and, on retaking the tests, found themselves locked out. Although this was not the ideal option, for there might be a slight improvement in pitch discrimination from multiple attempts, adding a single attempt restriction might discourage participants from contacting the author to have their access re-enabled. Participants were urged not to submit more than one complete set of responses, although anyone so doing would find ostensibly a new set of tests as the tone pairs were always offered in a randomized order. This randomization also prevented the answers being compared between participants.

[12] app.surveygizmo.com/login/v1 (accessed 15 May 2018)

The tests opened with a page giving an introduction and explanation of pitch discrimination as well as instructions on how to answer the questions. This was followed by two trial questions that allowed participants to familiarize themselves with the tests whilst setting a comfortable audio level on their computer (they were requested not to change this level during the test). Participants were then asked to provide their singing part from a list appropriate to their choir (the list included a ‘prefer not to say’ option). Twenty-two randomized test questions followed, an example page is shown in Figure 5.15. The bar graph shown towards the bottom of the page below the 'Next' button indicates progress through the tests. The survey concluded with a message thanking participants for their time and suggesting how they could find out more about online pitch discrimination tests if they were interested in testing themselves. To speed up the tests, each sound file started playing as soon as the page was opened (although there was a slight delay on slow networks while the file finished downloading). The file could be played as many times as wished by pressing the play arrow on the media player bar. It is appreciated that this might allow participants to improve their results but at the time there was no way of limiting the number of replays of the file. Having listened to the two tones the participant would select one of two options; ‘same’ or ‘different’, by clicking on the appropriate radio button, shown in Figure 5.15. They would then press ‘Next’ to move to the next test. Failure to select a radio button before pressing ‘Next’ would generate an error message requesting the participant select an answer before moving on – all 22 tests had to be completed at one time, incomplete tests could not be continued although they were stored but not used in the final analyses.

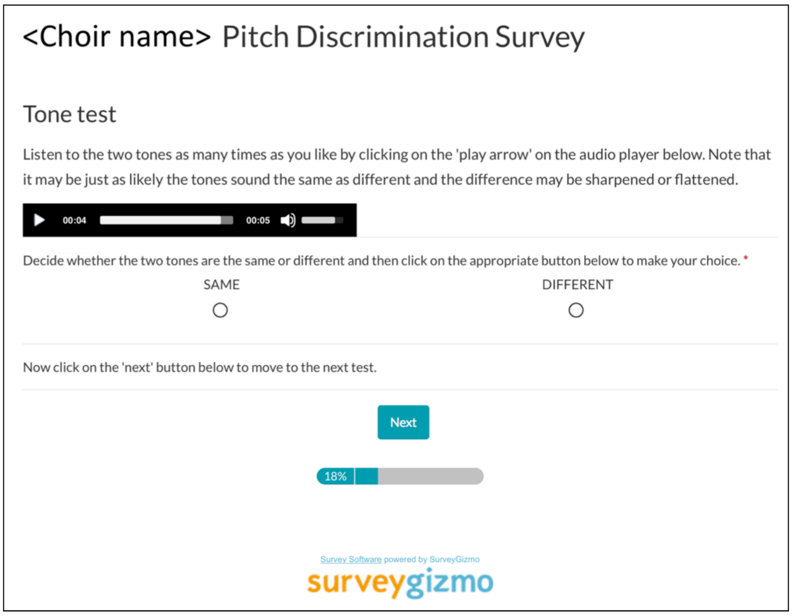


Figure 5.15 Example of a tone test page from the pitch discrimination tests. The media player is playing a sound file. The participant would click on one of the two radio buttons (white circles) to select whether they thought the two tones were the same or different

Piloting and publishing

Before publishing the tests a number of pilot trials were conducted with colleagues from the Open University. Listening tests of this kind are usually performed under strict environmental conditions to ensure any variations introduced by different audio systems, listening rooms, etc. are mitigated as far as possible. As pure tones (i.e. sinewaves) were being employed in this experiment it can be argued that the computer/audio system should make no difference providing audio conditions were kept the same throughout the test. The participants in the pilot were asked to take each test twice. On the first occasion they used a controlled set-up in a listening room with an *iMac* desktop computer, connected to the OU's internal network, running *Apple's Safari*® browser with *Sennheiser*™ *HD 380 Pro* headphones connected to the headphone socket of the computer. Once this test was completed the participant was asked to repeat the test at any location of choice using their usual method of listening to sound files on their networked system, computer, tablet or phone. They were warned that the order of the second set of tests would be different.

On completion of both tests the two results were compared. Any discrepancies were noted and the participant was interviewed to discover the experience of taking the tests in different locations. The overall results gave the reassurance that the computer system and location made no significant difference to the answers. However, the pilot did highlight one problem in using remote locations for the tests – delays in downloading the sound files. Having earlier established that there were no differences in pitch measurements when using uncompressed (wav) and compressed (MP3) sound files (sub-Section 5.3.2), it was decided to use MP3 sound files for the tone pairs. Using a 192 $kbits^{-1}$ high quality sampling rate, the file sizes were reduced by a factor of seven which resulted in a comparable reduction in download times. Once this change had been implemented and tested by the participants from remote locations, the choirs were sent their introductory letters. This letter included a website link (a *TinyURL*[13] was used for convenience) and a password, see Appendix 12. The results from the pitch discrimination tests will be described and analysed in Chapter 6.

5.4 Meeting the choirs

Once a choir agreed to take part in this research the author met with them at one of their regular rehearsals. There, the research was introduced along with opportunities for questions and a discussion about the causes of pitch drift (there was always a great deal of interest on the topic of pitch drift from the choir members). The experiment kit, shown in its travel case in Figure 5.16, was handed over to the singer running the experiments who signed for it, as it was the property of the Open University, see Appendix 13.

[13] tinyurl.com (accessed 15 October 2018)

Figure 5.16 The complete experiment kit in its travelling case, consisting of the audio recorder, an environment meter, spare batteries, USB computer lead, music and documentation

The operation of the audio recorder and environment meter were demonstrated and the paperwork introduced. To ensure a good balance of sound from the choir a suitable place was found in the rehearsal room for positioning the recorder. A brief test recording was made with the choir singing as loud as possible to ensure the microphone sensitivity setting was satisfactory. It was emphasized to the choir member that the chosen physical location should be used for each recording. No other recordings were made during this visit as *Test Piece* was new to all choirs and required to be practised before making the first recording. It was emphasised that once the choirs were familiar with both songs they must only be sung once and in the same order – *Test Piece* followed by their chosen song – and at about the same time in each rehearsal.

Finally, the physical size of the venue was measured and two impulse recordings made for subsequent analysis. The measurement microphone was placed where the musical director normally stood to conduct the choir. Recordings were made once any singer not wishing to be present during the recording of the balloon bursts had left the room. Two different positions for bursting the balloons were selected to avoid possible masking effects of the room and choir on the sound. A countdown was given prior to bursting each balloon to ensure the noise did not cause any sudden reaction from the singers, who were also asked to remain silent during and after the two balloon busts to avoid disturbing the results. Care was always taken to burst the balloons well behind the choir to ensure safety and the author wore safety glasses. The results from measuring the acoustic parameters of the rehearsal venues will be presented in Chapter 6.

5.5 Conclusion

Given that choral singing is one of the most popular pastimes – there are an estimated 37 million people in the European Continent including Russia taking part in some form of choral singing on a regular basis, representing one million ensembles (sub-Section 4.2.2) – there is a lack research in this area (Fischinger et al*.*, 2015).

This chapter has described the steps taken to obtain data from a series of rehearsals of amateur choirs based in the UK. The decision to work with the choirs in their own rehearsal environments is central to this research. The reason for collecting this data is to investigate whether pitch drift varies over a number of rehearsal performances of the same two *a cappella* songs. There is no evidence from the literature review (Chapter 3) that any similar research using amateur choirs to provide the data has been attempted before.

Drawing on the experience of the Open University in delivering distance teaching, which often involved the use of home experiment kits, it appeared feasible to ask choir members to undertake experiments to collect data during their rehearsals as long as the experiments were straightforward to run.

At each rehearsal, as well as making the recordings, a number of environmental factors were measured and logged, a register of attendance was taken and the musical director was asked to give an analysis of the rehearsal including an estimated rating of pitch drift. Singers were encouraged to take part in tests to measure their pitch discrimination abilities.

Once a choir completed up to twenty rehearsals the experiment kit, including the recordings and the completed paperwork, was returned to the author. After preparing and printing new customised documentation the refurbished experiment kit was taken to another choir. All the experiments eventually took 18 months to complete, starting in late June 2015 and ending in early December 2016. This period included breaks for bank and summer holidays and some unforeseen delays. However, the additional time required to complete the experiments did not impede the progress of the research.

The next chapter describes the analysis of the data. This includes the methodology used in rating the pitch drift of each song taken from the rehearsal recordings made by each choir. The statistical methods by which the pitch drift ratings were correlated against the variables measured at each rehearsal are described. The outcomes are used to determine whether there are any significant reasons why the pitch drifts on an irregular basis both within and from rehearsal to rehearsal when choirs are singing the same two *a cappella* songs.

Chapter 6
Testing the data

'Figures often beguile me, particularly when I have the arranging of them myself; in which case the remark attributed to Disraeli would often apply with justice and force: "There are three kinds of lies: lies, damned lies, and statistics."' (Mark Twain, 1906)

6.1 Introduction

This chapter introduces the analyses of the data collected from the experiments undertaken by the choirs that agreed to take part in this research. The chapter begins with an overview of the choirs recruited to participate in the research experiments described in Chapter 5. This is followed by an account of the past and current ways of measuring pitch. Two different applications for quantifying pitches in complex musical sounds are discussed and the justifications for using the particular application adopted for this research are presented. The rationale for using two discrete methodologies for assessing pitch drift, one quantitative and the other qualitative, is established and the procedures to rate pitch drift are explained. A detailed account is presented of the analyses made to determine if any correlation exists between the data sets for attendance, environment and pitch discrimination against the pitch drift experienced by the choirs at their rehearsals, along with the outcomes.

The following section introduces the choirs taking part in this research whilst respecting the anonymity granted to all choral practitioners who kindly agreed to take part.

6.2 Choirs taking part in this research

6.2.1 Choir types

A cohort of ten choirs was considered the minimum necessary to ensure that the data collected from their taking part in the research experiments would produce outcomes that could be considered significant (sub-Section 5.2.3). The main requirement of any choir recruited to this research was that they were familiar and comfortable with singing *a cappella* music. Before contacting any choirs, the results from the survey of choral practitioners, reported in Chapter 4, were used to assess which choir types would be the most appropriate to approach. In the survey respondents were asked for an estimate of the percentage of *a cappella* music sung by their choirs (sub-Section 4.3.2, Q8). The results revealed that choral societies, church and community choirs were less likely to perform *a cappella* music than chamber choirs, vocal groups and Barbershop or Sweet Adelines choruses (shown in Figure 6.1, which is a repeat of Figure 4.12). Consequently, the three choir types with the highest percentage of *a cappella* singing were approached to take part in the experiments (although any choir type willing to take part and which met the requirements for singing *a cappella* music was considered).

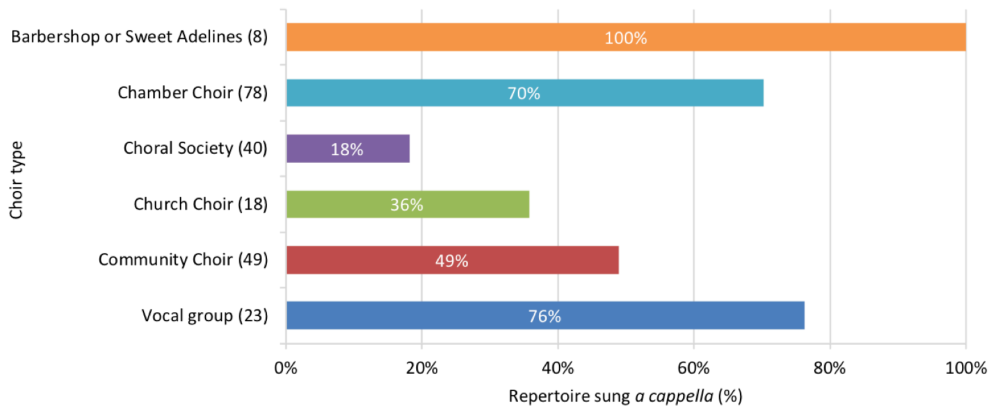


Figure 6.1 Percentage of *a cappella* music sung by choir type reported in the survey of choral directors (repeat of Figure 4.12) (total = 216)

6.2.2 Recruiting the choirs

The search for choirs was aided by the fact that the author and two colleagues sang in different chamber choirs, so it was only to be expected that their three choirs took part in the research. In fact, all the choirs apart from one were recruited through word-of-mouth contacts, which accounts in part for a cluster of choirs based around the Milton Keynes area, the home of the Open University. Only one choir contacted the team having read about the research in the *Association of British Choral Directors'* online *Newsletter*, where details of the research and a request for choirs to become involved had been published. A further four choirs initially offered to take part but withdrew for various reasons, whilst six choirs who were contacted either did not respond or felt unable to meet the exacting requirements of this research. Given the high level of commitment expected from the choirs it was gratifying that eleven choirs eventually agreed to become involved in the experiments. Brief (anonymous) details of these choirs are listed in Table 6.1. Their approximate locations in the United Kingdom may be recalled from Figure 5.4.

Table 6.1 Choir types, numbers of singers, rehearsals and useable recordings plus audition policies. To ensure anonymity, the order of choirs shown here is not the order subsequently used (total singers = 307)

Choir type	Number of singers	Number of rehearsals	Useable recordings*	Audition policy
Barbershop	26	20	20	Yes
Barbershop	22	16	12	Yes
Chamber	23	17	17	Yes
Chamber	26	12	12	Yes
Chamber	34	20	20	Yes
Chamber	25	20	20	No
Chamber	21	20	20	No
Chamber	26	18	13	No
Choral Society	71	20	20	No
Church	25	20	20	No
Vocal group	8	18	18	Yes
Totals	307	201	192	–

* Not all the rehearsals by the choirs delivered a complete set of data (i.e from 20 rehearsals)

Choirs with memberships of between 16 and 40 singers are generally referred to as chamber choirs[1]. Their repertoire typically covers a wide range of musical genres including a high percentage of *a cappella* music. Choirs with more than 40 singers are usually classed as choral societies. They take the opportunity to perform large-scale works such as oratorios and masses, usually with orchestral accompaniment. Choirs with fewer than 16 singers are often termed vocal groups or ensembles. They perform mostly *a cappella* music covering a wide range of musical genres. Church choirs often have small numbers of singers and whilst they may perform *a cappella* pieces on occasions, much of their singing is accompanied either by a keyboard instrument or a small instrumental ensemble. Their repertoire embraces early through to modern religious music. All these choirs have a minimum of four vocal parts; soprano, alto, tenor and bass (SATB) although all the parts may be doubled (SSAATTBB) for some works. Barbershop choruses[2] are traditionally but not exclusively male groups who sing in a low register. They also have four vocal parts comprising; tenor 1 (referred to as 'tenor'), tenor 2 (referred to as 'lead'), baritone and bass (TLBB).
Sweet Adelines are usually, but not necessarily, female groups using the same vocal part names as the Barbershop choruses but singing in a high register. Unfortunately, it was not possible to recruit any Sweet Adelines choruses to this research which was a pity given that both these two groups traditionally sing only *a cappella* music.

Anonymity of the choirs was assured at all times. In this thesis choirs are randomly named as 'Choir A', 'Choir B', etc. Likewise, their members are referred to in no particular order or vocal part as 'Singer A', 'Singer B', etc.

[1] classicalmusicreimagined.com/2016/04/01/quiz-type-choir-join/ (accessed 17 October 2018)
[2] www.barbershop.org/a-brief-introduction-to-voice-ranges-male-and-female-in-barbershop/ (accessed 25 November 2018)

6.3 Measuring musical pitch

In order to make any quantitative analysis of pitch drift it was first necessary to be able accurately to measure the pitch in samples taken from the choirs' recordings. This section opens with an overview of how pitch has been measured in the past before looking at current techniques.

6.3.1 A brief history of pitch measurement

Pikler (1966) refers to precise musical pitch measurement first being undertaken by Mersenne in 1636. Mersenne imagined a monochord, introduced in sub-Section 2.3.4, as a single-stringed instrument with both a fixed and a movable bridge, but having an impossibly large scale of 1000 increments set between the two bridges. This, he thought, could be used to demonstrate precisely the ratios of the twelve tones of the scale in the 'mean tone' tuning system (the forerunner of today's equal temperament tuning) found on the keyboard instruments of his time. By 1701 Sauveur had redefined musical intervals as frequencies rather than Mersenne's 'vibrating sections' (ratios) of a monochord string (Maxham, 1976). Numerous machines incorporating monochords, tuning forks and reeds, were devised to generate required frequencies and thereby enable pitches to be compared. By the nineteenth century Helmholtz (1877, p. 36–45) had developed sets of *resonators* that bear his name, pictured in Figure 6.2.

Figure 6.2 A series of *Helmholtz resonators* c. 1860s (© Smithsonian Institute)

These *resonators* consist of a series of vessels or jars with precise volumes, constructed of brass, and with openings at the top of a narrow (pointed) neck and wide open at their base. They resonated (i.e. amplified the sound) at fixed notes in the musical scale and were engraved accordingly with the note value (pitch). When the top was held to the ear a particular frequency within a complex sound could be heard if resonance occurred. Sets of *Helmholtz resonators* were made to be used as discrete acoustic filters in the analysis of pitch in complex sounds.

Measuring pitch mechanically was first achieved with Scott and König's *Phonautograph* (1860) where the vibrations of a diaphragm were transmitted by levers and a stylus to a smoked paper strip attached to a revolving drum (Helmholtz, 1877, p. 166). This resulted in a linear trace on the paper strip, shown in Figure 6.3, varying as the amplitude of the vibrations with the period between them being measured to obtain the frequency.

Figure 6.3 An example of a trace from König's *Phonautograph*

A similar apparatus was used by Cornu and Mercandier to make a series of measurements on the voice (Helmholtz, 1877, p. 325). However, Edison's *Phonograph* of 1877 produced sound recordings in wax which were far more permanent than traces on smoked paper (OpenLearn, 2018). The 'hill-and-dale' indentations in the groove made by the sounds could be measured optically. Taking a radically different approach, König developed the *Manometric flame apparatus* in which sounds modulated a luminous gas flame. This modulation was measured using a variable speed drum-mirror stroboscope (Helmholtz, 1875, p. 374). The frequency of the sound could be calculated from the rotational speed of the drum, once it was adjusted so that the flame appeared stationary. This apparatus was incorporated in Seashore's original *Tonoscope* of 1902 with a later system being used to measure an individual singer's control of their vocal folds. Eventually, electronic systems including Seashore's *Tonoscope* of 1930 (Figure 6.4) allowed far more accurate measurements of pitch (Seashore, 1938, p. 362).

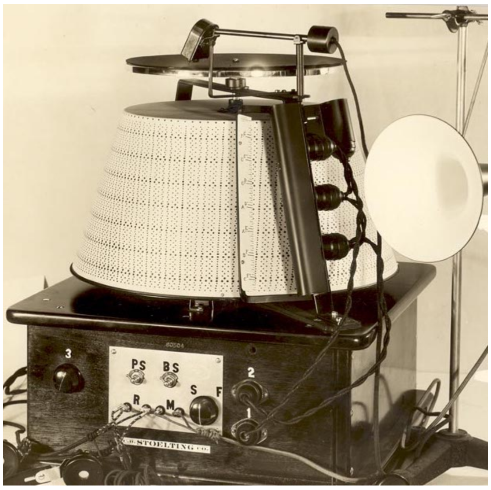


Figure 6.4 Seashore's *Tonoscope* c. 1930s, (© Smithsonian Institution)

Whilst it was possible to identify the individual notes of a solo performer within a musical melody with *Helmholtz resonators* or Seashore's *Tonoscope*, identifying individual pitches within a chord was a far more difficult task. Ternström (2002, p. 1) refers to Lottermoser and Meyer (1960) as being the first to undertake work on the sounds of choirs. They used 'a special search-tone analysis' with complex narrow-band (1 Hz) filters involving modulation techniques to analyse commercial recordings of three well-respected professional *a cappella* choirs to study the intonation of simultaneous intervals. The number of recordings analysed is not known. Lottermoser and Meyer found a large variation in the intervals in the chord, major thirds being too wide whereas minor thirds were too narrow. Fifths were close to just intonation tuning with a spread of pitch of 25 cents. This would be expected if they were performing using equal temperament tuning, see Table 2.1 of sub-Section 2.3.4.

6.3.2 Pitch measurement today

Much research has involved specialist singing groups working under controlled laboratory conditions, e.g. Jers and Ternström (2004), Howard (2007), Mauch *et al*. (2014) and Fischinger *et al*. (2015). Analysis has used phonetic software such as *spead*[3] by Laryngograph® and *Praat*[4]. By the end of the 20th century vocal processors such as *Auto-Tune*® from Antares Audio Technologies[5] were capable of correcting off-key inaccuracies and shifting the pitch to the correct equal-temperament semitone. A version of *Auto-Tune* was even capable of correcting the pitch in live performances but only for a solo singer. Digital audio workstation (DAW) computer applications, such as *GarageBand*® by Apple Inc. and *Cubase*® by Steinberg Media Technologies GmbH, allow music composition, recording, arranging, editing and mastering digital audio files and can also include pitch correction using plug-in modules. Audio editing software such as *Audition® CS6* from Adobe Inc.[6] provides powerful audio processing effects such as amplifiers and filters as well as a spectral pitch display which shows the pitches that comprise a chord. Additionally, *Audition's* frequency analysis tool displays a waveform in the frequency domain allowing both the frequency content and musical pitches to be measured. Increases in the processing capabilities of personal computers and tablets have made possible sophisticated real-time pitch recognition applications. For example, the vocal training application *Sing&See*© from Cantovision Ltd[7] offers real-time visual feedback of a singer's voice, but still only works with a single vocal part. However, the software application that sets itself apart from those mentioned above is *Melodyne Studio*® from Celemony Software GmbH[8]. Designed for the post editing of pitch, vibrato, amplitude and timing of musical notes (rather than waveforms) of any digital audio recordings, *Melodyne* can work with complex multi-part music to

[3] www.laryngograph.com/pdfdocs/UseofSpeechStudio.pdf (accessed 30 May 2018)
[4] www.fon.hum.uva.nl/praat/ (accessed 30 May 2018)
[5] www.antarestech.com (accessed 30 May 2018)
[6] www..com/uk/products/audition.htmls (accessed 30 May 2018)
[7] www.singandsee.com (accessed 30 May 2018)
[8] https://www.celemony.com/en/melodyne/what-is-melodyne (accessed 30 May 2018)

recognise and decompose the sounds into individual musical notes; the properties of which can be measured and changed. Celemony calls the process of decomposing the sound *Direct Note Analysis*™ (*DNA*). *Melodyne* provides a graphical display of the decomposed sounds as musical notes which are termed 'blobs' in Celemony's own terminology.

For this research the measurement of the exact pitch of musical notes within a chord, including any offset values in cents, was essential for making quantitative analyses of pitch drift in the rehearsal performances of the choirs. Furthermore, the pitch can be re-evaluated – useful if any queries on pitch drift assessments occur. This is not always the case with qualitative judgements as experience has shown individuals may come to a different conclusion when assessing pitch drift on a subsequent occasion. However, quantitative assessments of pitch are far from straightforward so, after careful consideration of the various qualities and features of available computer applications for measuring musical pitch, both *Audition* and *Melodyne* were selected for further investigation as contenders for use in this research.

6.4 Quantifying pitch in this research

6.4.1 Recordings made by the choirs

The recordings of the choirs made at each rehearsal (sub-Section 5.3.2) were returned to the author at the end of the experimental period (i.e. up to 20 rehearsals). The audio files containing the recordings were date stamped when made so they could be reconciled subsequently with the attendance and environmental data for each rehearsal. Rehearsal numbers replaced dates for the analyses of the data as this allowed standardisation between choirs which would be impractical with dates. A total of 192 digital audio recordings out of a possible 220 were received from the eleven choirs taking part in this research (Table 6.1). This was lower than hoped for as not all musical directors felt able to complete twenty recordings. Reasons such as '…ensuring singers would return in the Autumn if we stop now…', were offered! This was understandable, if unfortunate, as the musical directors may well have undertaken commitments for which rehearsal time was urgently required whilst being involved with the experiments. However, the minimum number of rehearsals completed by any choir was twelve, which was thought at the time to be sufficient to give significance to their results.

Each recording included a performance of *Test Piece* (the piece specially composed for this research, described in sub-Section 5.3.4) and the choir's chosen song – which is how these two pieces are being identified in this thesis. Copies of the scores for the two versions of *Test Piece* (one for SATB choirs along with another set for low register TLBB Barbershop choruses) together with the list of the chosen songs may be found in Appendices 8 and 9. Additionally, synthesized versions of *Test Piece,* in both piano and chorus renditions, may be found on the audio CD which accompanies this thesis.

6.4.2 Determining pitch drift

Determining whether any pitch drift occurred in either or both of the two songs sung by the choirs at each rehearsal is central to this research. All measurements of pitch will be based on an equal temperament scale using concert pitch (A_4 = 440 Hz). Assessing pitch drift requires knowledge of two pitches, one at or near the beginning of the song and the other at the end. Pitch drift is determined by the difference between these two pitches. An initial pitch was always provided to the choirs by the musical director or accompanist using a pitch pipe, piano note, spread chord, etc.

It was expected that the responses from each musical director's questionnaire (sub-Section 5.3.6) would include a qualitative judgement of pitch drift for all songs, but this proved not to be the case with several choirs, as will reported on later in this chapter. The quantitative method of measuring pitch drift, discussed in sub-Section 6.4.4, would provide a consistent set of results for determining pitch drift. The plan was to combine the two sets of results for use in subsequent statistical analyses. However, as already noted in the previous section, the measurement of pitch either as frequency or note value plus offset in cents is not straightforward. The pitch of a pure tone may be measured relatively easily and even a single note containing harmonics is not problematic. However, the combinations of pitches that comprise a musical chord makes the measurement of an individual pitch, which is critical to this research, challenging. This is because there are not only a number of harmonic rich sounds but also several singers to each vocal part who are singing (or believe they are singing) the same note.

6.4.3 Characterising pitches and pitch drifts

A musical sound is measured in terms of note names (A, B, C … G) and octave numbers (0, 1, 2 … 8) that position the sound on an ascending musical scale, low to high (sub-Section 2.3.4). When using equal temperament, the pitch distance between two adjacent notes (i.e. a semitone) is 100 cents and the precise pitch of any musical sound may be represented by the name and number of the note plus the number of cents the sound deviates from the exact musical note. This same musical sound may also be represented by its fundamental frequency (f_0) in Hertz. For this research a decision was made to work with equal temperament pitches in standard musical notation rather than frequencies (although frequencies may be referred to on occasions) with the note name and octave number along with any deviation from the note value in cents. For example, in equal temperament, and using A_4 = 440 Hz, the note C_4 has a frequency of 261.63 Hz whereas the note C_4 +10 cents is 263.14 Hz and the note C_4 –10 cents is 260.12 Hz. Describing a note value in terms of cents from the required pitch makes the drift more obvious than quoting a frequency which would need to be referenced against that of the note. In terms of accuracy a decision was taken to use one cent as the smallest increment, giving a precision to one percent. As the average ability of humans to discriminate between two pitches based around A_4 is 12 cents (Seashore, 1938, p. 56), this gives a good margin of tolerance for the results.

6.4.4 A comparison between *Audition* and *Melodyne*

To be assured of using the most suitable computer application to measure pitches of complex waveforms such as musical chords a direct comparison was undertaken between the two contenders for this task that had been identified earlier – *Audition CS6* and *Melodyne Editor V2*. Both applications were run on an *Apple® MacBook Pro* (15-inch late 2011) running an *OS X 10.10* (*Yosemite*) platform. The first comparison used a specially prepared audio test file and this was followed by a second comparison using a recording from one of the choirs.

Preparing the audio test file

Using the tone generator tool from *Audition*, an audio test file was constructed comprising the three separate notes of the equal tempered C major triad plus the octave note (see Figure 6.5). Equal temperament was used to ensure the notes would not have a simple frequency ratio between them (apart from the octave) – i.e. they would not be phase locked – thus reflecting more closely the situation in which pitches would need to be measured for the research. Each note, detailed in Table 6.2, comprised a pure tone with a duration of one second. To ensure no overloading when the tones were mixed into the chord the initial amplitude of each note was set to –20 dB. The tones were assembled in an ascending sequence starting with note C_4 (261.63 Hz), allowing a half second interval of silence between each note. The sequence was followed by a four second chord comprising all four tones mixed together. Cosine S-curve fading was then applied to the beginning and end of each note and to the chord. The level of the resulting waveform was normalized to an amplitude of –1 dB and saved as both a 16-bit uncompressed wave file and a compressed MP3 file with a bit rate set to 192 kbs^{-1}, both with standard sampling rates of 44.1 kHz.

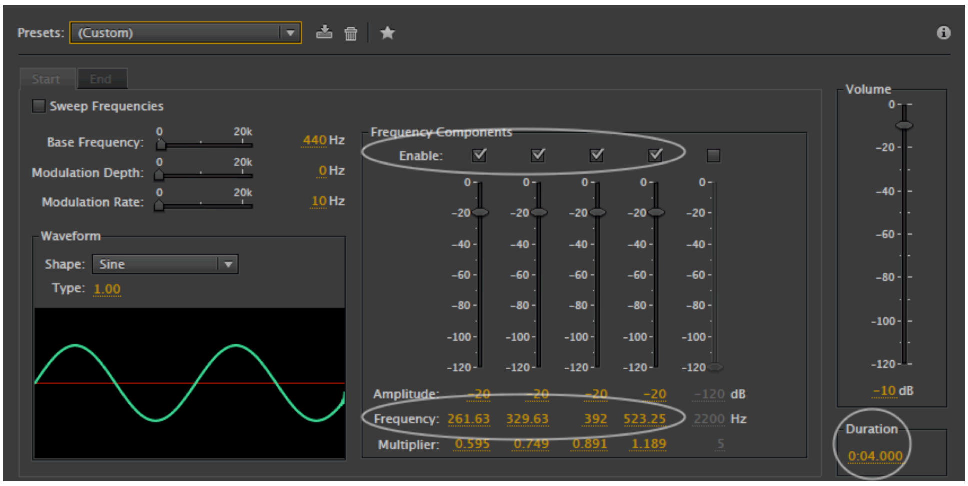


Figure 6.5 Settings on the *Audition* tone generator tool for the four second C major chord

Table 6.2 Note values and frequencies forming the equal tempered C major triad plus the octave. (The frequencies have been rounded to 2 places of decimals for use in *Audition*'s tone generator, Figure 6.5)

Note	Frequency (Hz)
C_4	261.63
E_4	329.63
G_4	392.00
C_5	523.25

Pitch analysis using Audition

Audition has three display modes in the time domain: waveform; spectral frequency; and spectral pitch. Each may be displayed alone or any two together. In Figure 6.6 the spectral pitch display is shown in the window below the size-reduced waveform display. The spectral displays are derived from a Fast Fourier transform (FFT) analysis which calculates the frequency components of the waveform by sampling it at a specified number of points (the FFT size) – the more samples made the more accurate the analysis becomes.

The waveform display at the top of Figure 6.6 shows the amplitude/time envelope view of the sound. Below, the spectral pitch view displays musical-notes/time. The pitches (notes) are shown in blue with the scale of the note values shown on the far right-hand side. This display also shows the harmonic components within the waveform using colours ranging from yellow for high-level through orange/red for mid-level to brown for low-level amplitudes of the harmonics. The four individual tones to the left of the waveform are represented by four blue lines within the spectral display and correspond to the four individual notes. The slight orange shading apparent at the beginning and end of each line is due to the introduction of spurious harmonics due to cosine S-curve fading at the start and end of the sound (this is where they are most apparent). When the four equal tempered pure tones (shown in blue on the left of the display in Figure 6.6) are combined into the chord, shown on the right of the display, *Audition* displays the 'missing fundamental' root note C_2. This has been added into the spectral pitch display in blue by *Audition's* analysis algorithm for completeness (it doesn't exist either in the sound itself or in the frequency analysis display of the chord in Figure 6.7(b)). Note C_2 is displayed because the four notes in the chord (C_4, E_4, G_4 and C_5) are the 4^{th}, 5^{th}, 6^{th} and 8^{th} harmonics of a note with f_0 of 65.41 Hz. Recognised as harmonics, the four individual notes are now displayed in orange (indicating they are notes of a scale) rather than blue (signifying a root note).

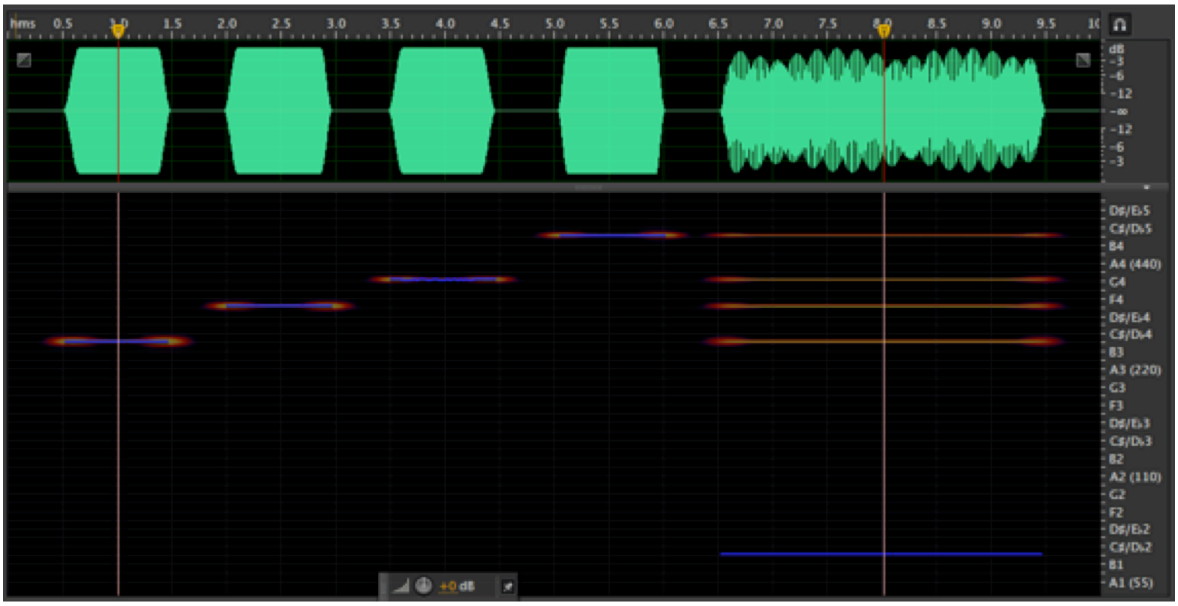


Figure 6.6 *Audition*'s spectral pitch analysis with the waveform shown in green – the blue lines display the pitch (note) of each waveform, the orange lines represent harmonics (see text). (This figure uses two screenshots to show both the 1 s and 8 s sample points)

It is not possible to interrogate the individual waveforms to read the exact frequencies from this display, just the note value from the right-hand vertical scale. However, note values and offsets plus frequencies can be obtained by using *Audition's* frequency analyser tool. This tool was used to take two FFT analyses; firstly on the waveform with the cursor positioned at the 1 s point, then at the 8 s point (represented by the two vertical cursor lines shown in Figure 6.6). The frequency curves resulting from the two FFT analyses are shown in Figure 6.7. The FFT analysis takes audio samples equally from either side of the cursor position. Choosing an FFT sample size of 32768 will ensure only data from the single tone will be sampled, with the spurious frequencies at either end of the note being ignored, as long as the cursor is positioned in the middle of the waveform. This assures an accurate result in the frequency analysis window (the sample rate is 44,100 per second so an FFT sample size of 32768 represents 0.74 s which fits within the 1 s duration of the single tones). The frequency analysis window shown in Figure 6.7(a) displays the single frequency of 261.67 Hz and the musical note C_4 with no deviation (0 cents), shown circled below the frequency chart. Figure 6.7(b) shows the frequency analysis of the complex waveform; the cursor being set at the 8 s analysis point. Here all four waveforms are displayed but although both a frequency and a pitch value are given (ringed at the bottom of the figure) the value corresponds to just one of the four frequencies present in the sample. No other exact frequency and note value may be found directly from this display although approximate values may be found by placing the cursor anywhere on the display window as discussed below. However, this method of examining a chord would be of little help in analysing the recordings of the choirs.

Expanding the amplitude and frequency axes in the analysis window allows the peaks of the frequency components in the complex waveform to be accurately measured (Figure 6.8(a)). Note E_4 (329.45 Hz) has the greatest magnitude of the four displayed at –12.58 dB – most likely due to some artefact in the analysis algorithm (the levels should all be

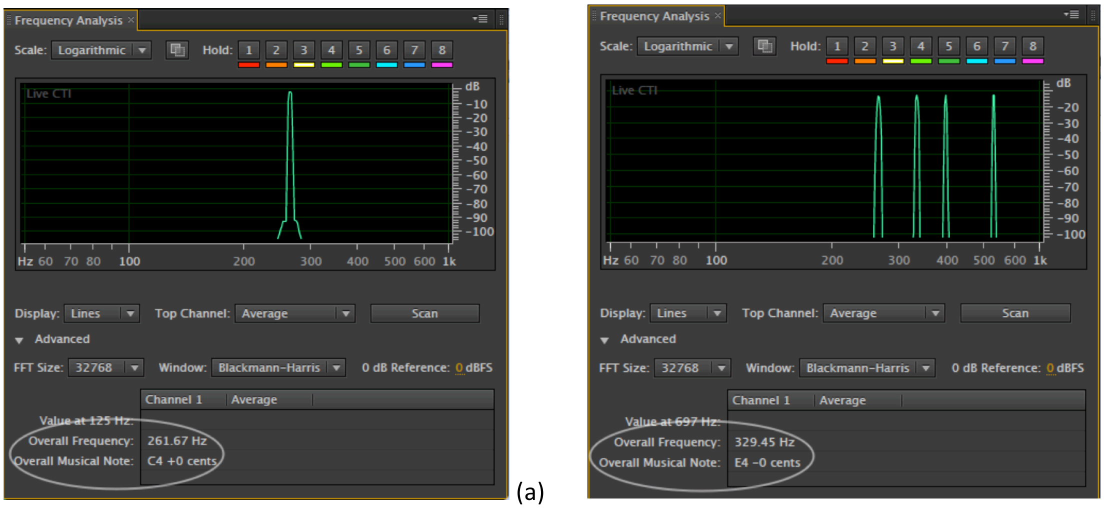


Figure 6.7 (a) Frequency analysis display of a single note; (b) frequency analysis of a complex sound containing all four notes in the chord. (The missing fundamental of C_2 (65.41 Hz) is not displayed here)

identical) – which is why this frequency and note value is recorded in the results box (ringed in Figure 6.8(a)). Expanding the frequency axis to its maximum extent in the analysis window of Figure 6.8(b) allows a measurement of the frequency of each note by placing the cursor at the peak of each frequency component of this complex waveform, shown here as a white arrow.

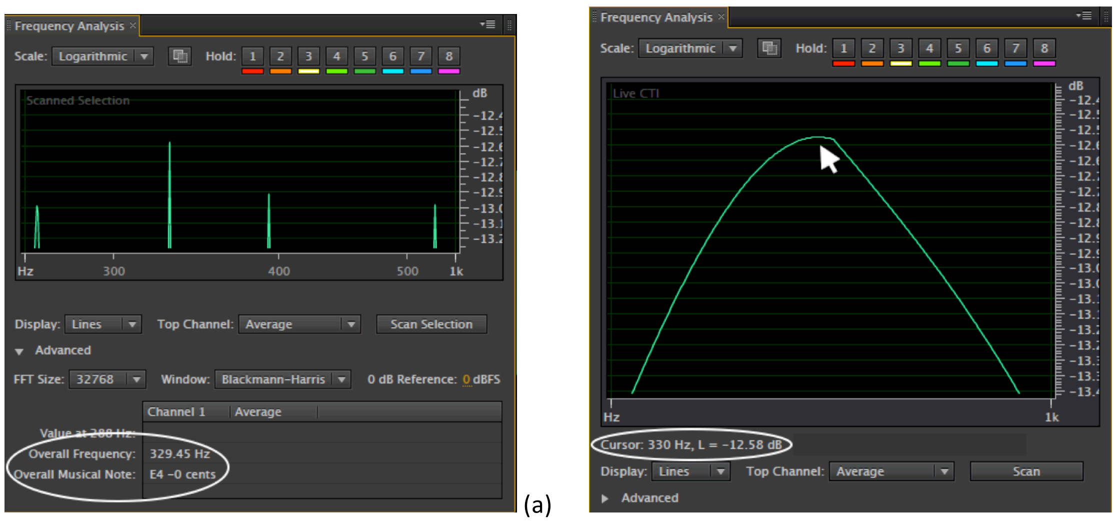


Figure 6.8 (a) View of Figure 6.7(b) with an expanded amplitude scale showing that note E_4 has the highest peak amplitude (frequency = 329.45 Hz , note = E_4 –0 cents); (b) measuring the frequency by expanding the frequency scale while keeping the expanded amplitude scale as in (a) and placing the cursor at the peak of the curve of note E_4. The result (330 Hz, –12.58 dB) is ringed

Unfortunately, this method only gives a value of frequency to the nearest integer value (330 Hz) plus the peak amplitude (–12.58 dB) as shown ringed in Figure 6.8(b). Notice also that the musical note value and offset is not given using this form of the frequency analysis so that, added to the approximation to the frequency, this is an unsatisfactory method of measuring pitch for this research.

To achieve more accurate measurements of the individual notes in the chord it is necessary to filter the sound so that only the frequency of interest remains, the others being reduced in amplitude. This allows just the note in the chord to be displayed in the frequency analysis window which can then be measured as demonstrated in Figure 6.7(a). The filtering uses *Audition's* passband filter tool, the set-up window of which is shown in Figure 6.9. The centre frequency is set to that of the note to be analysed with the passband sufficiently narrow to ensure that the other three notes in the complex waveform (chord) of Figure 6.7(b) are attenuated so having a negligible effect on the analysis. The filter can also be set modify the amplitude of the frequencies within the pass-band, which can be very useful, although here the level is set to 0 dB. While this method works well with pure tones, it is more difficult to use with sounds produced by the human voice as will be demonstrated in sub-Section 6.4.5.

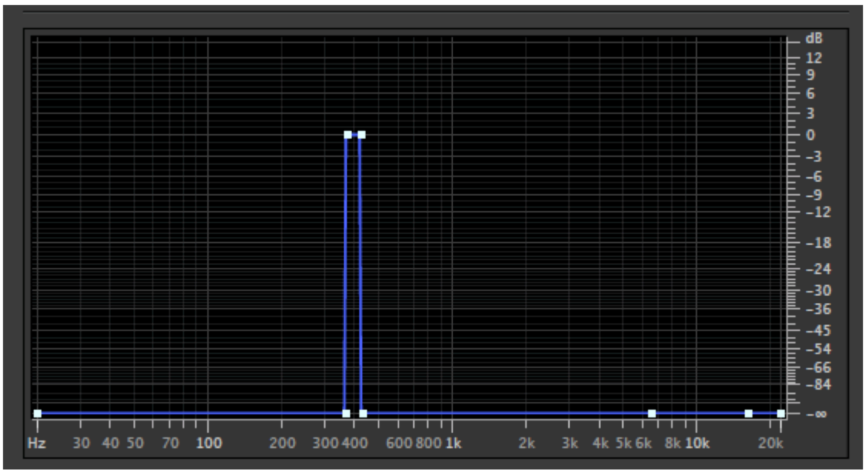
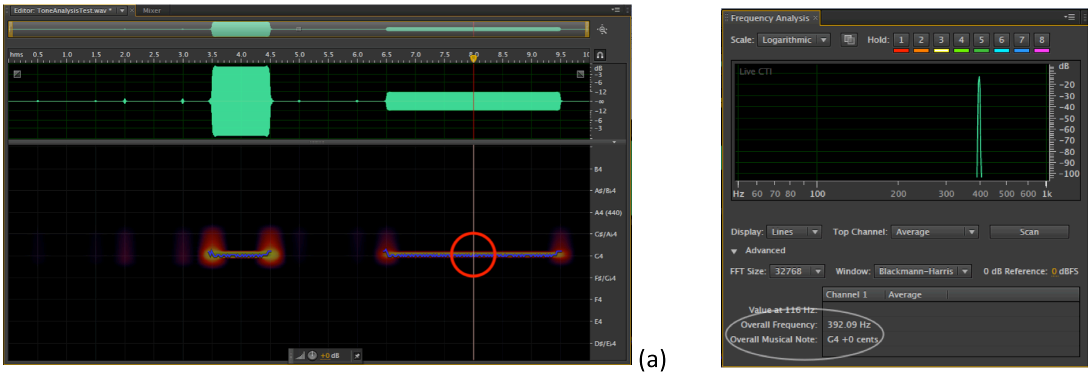


Figure 6.9 Setting the FFT passband filter centred on 392 Hz (note G_4)

To analyse the chord in this example four passband filters were constructed, each with centre frequencies based on the note frequencies shown in Table 6.2. Each filter was applied in turn to the original waveform displayed in Figure 6.6 and sampled at the 8 s test point as before. Figure 6.10(a) shows the result of using a filter centred on note G_4 (392 Hz). This returned a frequency curve with a measured frequency of 392.89 Hz and a note value of G_4 with no deviation (0 cents) shown in Figure 6.10(b). The blue line now allotted to this pitch demonstrates that *Audition* now recognises the note as the fundamental G_4 and no longer a harmonic component of the original C_2 chord.



(a) (b)

Figure 6.10 (a) The result of applying a G_4 passband filter; (b) the waveform at the cursor position (circled in (a)) with the information about the note shown below (circled)

This process was repeated for all four frequencies giving the results shown in Table 6.3.

Table 6.3 Pitch analysis results from *Audition* (frequencies were not used in this research)

Note	Actual frequency (Hz)	Measured note	Measured frequency (Hz)
C_4	261.63	C_4 +0 cents	261.7
E_4	329.63	E_4 +0 cents	329.5
G_4	392.00	G_4 +0 cents	392.1
C_5	523.25	C_5 +0 cents	523.1

This method of analysis was very time-consuming when analyzing a simple chord based on pure tones and would prove even more so when dealing with the complex sounds produced by a choir. However, it was considered necessary to demonstrate why a more direct approach to pitch analysis had to be taken. The following sub-section demonstrates how *Melodyne*, introduced in sub-Section 6.3.2, proved to be a far more satisfactory choice for pitch analysis in this research.

Pitch analysis using Melodyne

In comparison to *Audition*, taking the same measurements using *Melodyne* is remarkably straightforward. The same sound file used to test *Audition* was opened using *Melodyne's* default *polyphonic analysis algorithm* for pitches of equal temperament. This algorithm decomposes complex sounds into individual notes, referred to as blobs (sub-Section 6.3.2). The results of running this algorithm on the sound file are displayed in Figure 6.11.

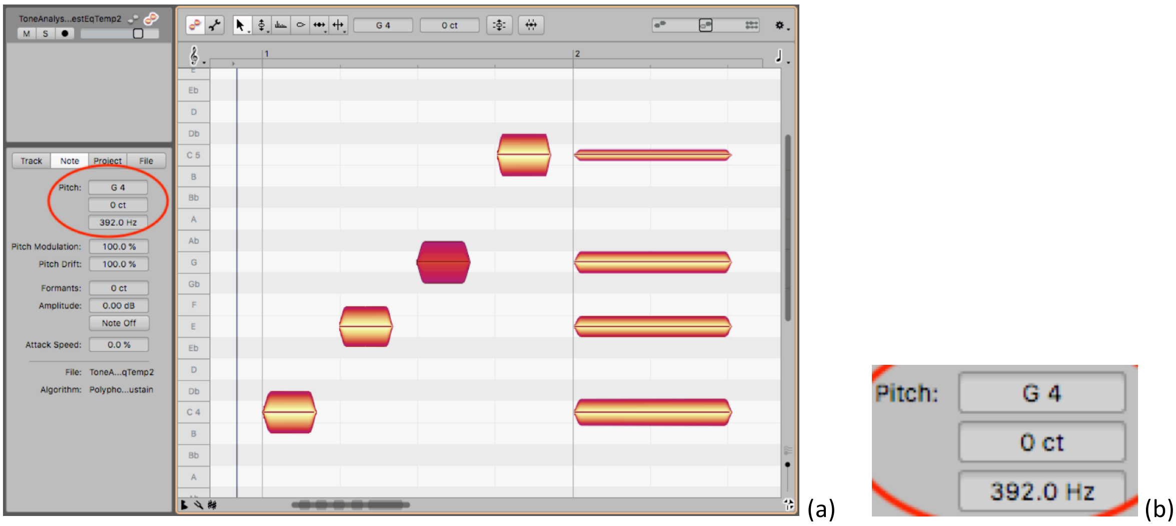


Figure 6.11 (a) *Melodyne*'s polyphonic analysis window (note the similarity to *Audition*'s spectral pitch analysis window in Figure 6.5) – the values of the selected blob (in red) is shown to the left (ringed) and the reduction in amplitude of the tones above C_4 is due to the combining of the four tones to make a chord; (b) detail of the note's pitch and frequency values

This shows a display with similarities to the spectral pitch display of *Audition* (compare with the spectral pitch window in Figure 6.6). One difference is that the height of each blob in the *Melodyne* display of Figure 6.11(a) represents the amplitude of the sound, with the length of the blob representing time (and tempo which will not be used).

The huge advantage of *Melodyne* is that the analysis of a note is achieved simply by clicking on a blob (highlighted in red), giving the result displayed in Figure 6.11(b). Table 6.4 shows the results from *Melodyne* alongside those from *Audition* (taken from Table 6.3 and shown in grey).

Table 6.4 Comparison of results pitch measurement from *Audition* and *Melodyne*

Note	Frequency (Hz)	*Audition* note	*Audition* (Hz)	*Melodyne* note	*Melodyne* (Hz)
C_4	261.63	C_4 +0 cents	261.7	C_4 +0 cents	261.6
E_4	329.63	E_4 +0 cents	329.5	E_4 +0 cents	329.6
G_4	392.00	G_4 +0 cents	392.1	G_4 +0 cents	392.0
C_5	523.25	C_5 +0 cents	523.1	C_5 +0 cents	523.3

Both applications returned the correct note values. *Audition's* frequency measurements were given to two places of decimals which have been rounded to one place for comparison with the results for *Melodyne.* However, as this research is working with note values and cents rather than frequencies (sub-Section 6.4.3) *Melodyne's* difference in the precision of the frequency results, which is under 1%, is not seen as a disadvantage.

Pitch measurement with compressed files

The pitch comparison tests described above were undertaken using an uncompressed wave sound file. The same tests were also run using the compressed MP3 sound file, described earlier in the sub-section, to ensure that the compression algorithms had no effect on the pitch. Exactly the same pitch values were measured as those shown in Table 6.4 confirming that the use of compressed files was acceptable for this research. This was an important result as, for data storage efficiency, compressed files were to be used for recording the choirs, as described in sub-Section 5.3.2 and in the pitch discrimination survey, described in sub-Section 5.3.7.

Summary of the two applications

The comparison between *Audition* and *Melodyne* used a complex waveform of equal tempered pure tones to demonstrate how both applications can be used to measure individual frequencies within a complex musical sound. *Audition's* passband filter settings ensured the frequency of the pure tone to be measured was within the pass-band. The filter will eliminate the unwanted frequencies whilst allowing the required frequency to be analysed and even amplified if necessary. However, a further complication arises where notes are sung simultaneously by individual singers who may vary slightly in pitch, possibly requiring filters with slightly different passbands. Whilst the process of setting up filters might be somewhat simplified using *Audition's* automation tools, it would be a laborious task when analysing the large number of recordings created by this research. In contrast to this, the simplicity of using *Melodyne*, which produced equally reliable results, cannot be matched. So the decision was taken to adopt *Melodyne* following an assurance that it worked equally well with musical sounds produced by choirs. This is the subject of the next sub-section.

6.4.5 Pitch analysis of the choirs' recordings

Whilst the use of *Melodyne* has been demonstrated to be ideal for analysing a combination of pure tones, it was felt necessary to confirm that it is appropriate for use in analysing the pitches sung by an actual four-part choir, where the singers of each part should each be singing the same musical note – but as will be shown this is not necessarily the case. A fragment of *Test Piece* arranged for lower voices (the tenor G clef has the figure 8 at the bottom indicating the notes are an octave below the usual treble G clef) is shown in Figure 6.12. (The complete score may be viewed in Appendix A8.2) The frequency analysis of a sample recording of a Barbershop chorus singing this fragment of *Test Piece* is displayed using *Audition* in Figures 6.13 and 6.14 and using *Melodyne* in Figure 6.15. The note $E\flat_3$, ringed in Figure 6.12 (both notes are the same), was measured with both applications. *Audition* reported this note to be D_4 +30 cents whereas *Melodyne* measured it as D_4 +28 cents. This should be the note $E\flat_3$, but the pitch has flattened by 72 cents ($E\flat_3$ –72 cents is the same as D_3 +28 cents). This degree of pitch drift was typical for many of the choirs at some of their rehearsals. Moreover, it was often the case that the first note sung was some way away from the note given by the musical director before the singing started. Whilst not directly pertinent to pitch drift this finding will be commented upon in Chapter 7.

Figure 6.12 Fragment of *Test Piece*© set for the lower voices of Barbershop choruses (with permission) – the note circled ($E\flat_3$) corresponds to the those circled in the *Audition* and *Melodyne* displays in Figures 6.13 and 6.15 respectively.

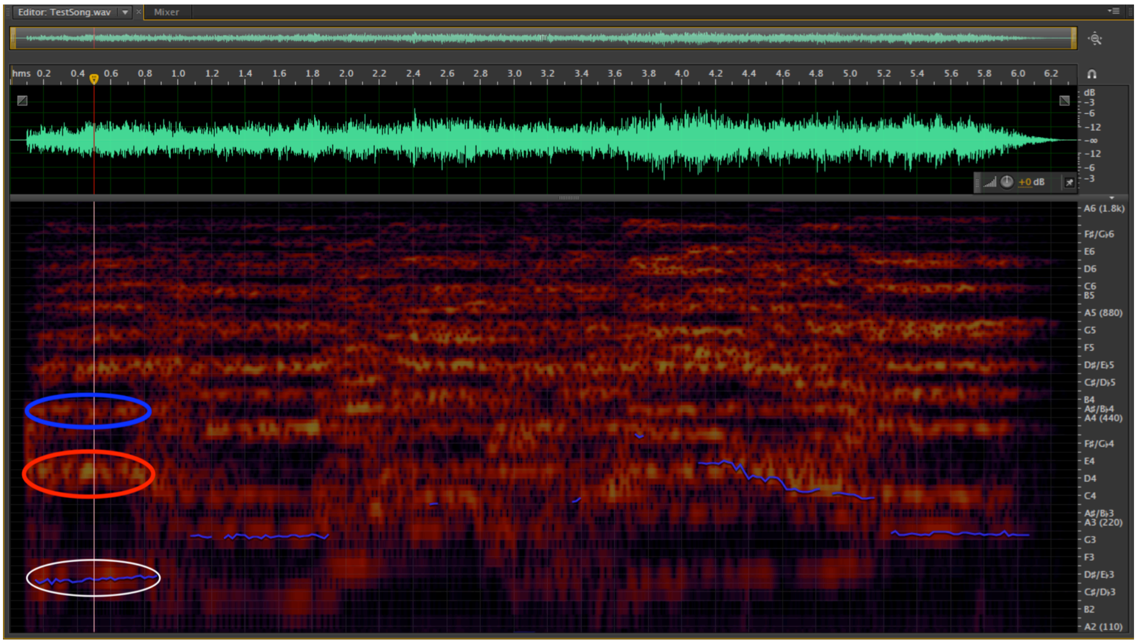
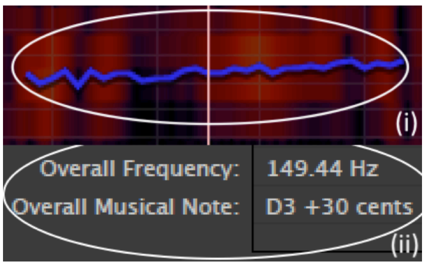


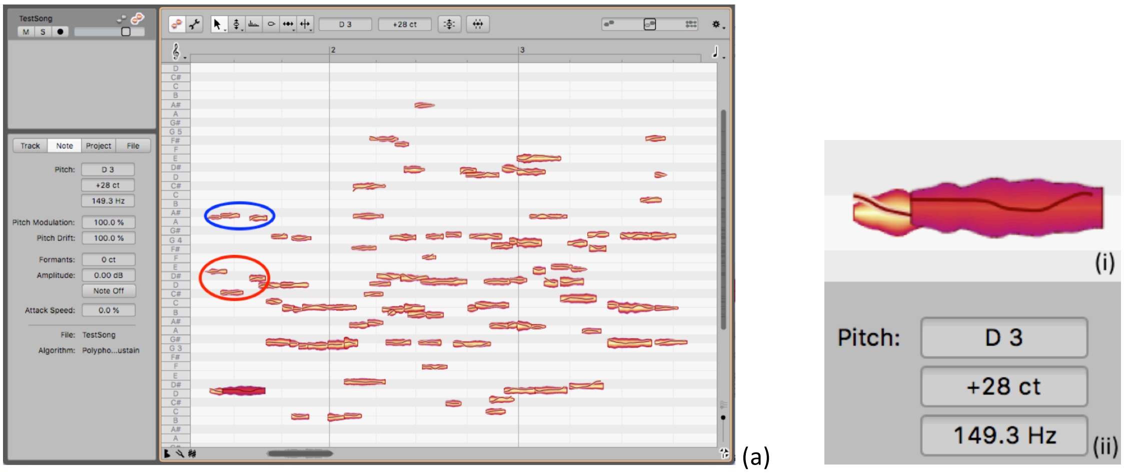
Figure 6.13 Audition's decomposition of a clip from a recording of a four-part song, (notes ringed)

(a)



(b)

Figure 6.14 (a) Frequency analysis of the note at the cursor position (ringed); (b)(i) the trace of the pitch at the analysis point (from Figure 6.13) and (b)(ii) the pitch and frequency at the analysis point



(a) (b)

Figure 6.15 (a) *Melodyne*'s decomposition of a clip from a recording of a four-part song; (b)(i) the 'wavy line' describes the precise path traced by the pitch[1] and (b)(ii) the pitch and frequency of the blob highlighted in red

Comparing Figures 6.13 and 6.15(a), both applications show a number of notes and/or harmonics to be present in this complex sound. Figures 6.14(b) and 6.15(b) show pitch measurements of the note under scrutiny (ostensibly $E\flat_3$) to be within two cents of each other. (When measuring low pitches such as note $E\flat_3$ a measured frequency difference of around 0.1 Hz can cause a 1 cent change in the note value.) Slight differences may be caused by rounding errors in the measured frequency. As mentioned earlier, when using *Audition's* frequency analysis only the pitch measurement of the highest amplitude is directly available (in this case the root note). However, using suitable pass-band filtering the values of the other sung note, which appears as a harmonic in *Audition's* display, may be measured (ringed in red in Figure 6.13).

Melodyne has recognized possible changes in the tenor vocal part singing $E\flat_4$ within the period of this note, shown as a cluster of three notes ringed in red in Figure 6.15(a). This indicates the notion of pitch drift in choirs to be problematic as there can be considerable variability of pitch within a part. *Audition* recognises pitches as harmonics around $A\sharp_4$, ($B\flat_4$ or the 2nd harmonic of $E\flat_3$), ringed in blue in both Figures 6.13 and 6.15(a). *Melodyne* has also recognised these pitches but as sung notes (and indeed they may well have been sung in error). However, as they are not in the *Test Piece* score, they would not be considered in the measuring pitch drift. In fact, *Audition* shows many more harmonics up to note A_6, but *Melodyne* does not recognise any of these additional pitches as sung notes. Melodyne's polyphonic algorithm appears to be able to distinguish between pitches as harmonics and those of sung notes. This may be because sung notes will not be in phase with the fundamental as would be the case with harmonics. However, this is conjecture as, quite understandably, Celemony Software GmbH apologised that they were unable to divulge any technical information regarding the detailed processes of *Melodyne*. Figure 6.15(b) highlights a variation in the pitch line within the blob but again no information was available on how the pitch rating for the blob is reached. It is assumed that the same method of pitch rating is applied to all blobs making a measurement of pitch drift between blobs reliable even if the absolute values of pitch change within each blob. This highlights how problematic the measurement of pitch drift is in reality given that human judgement may well identify another part of the chord on which to make a pitch rating. This will be discussed further in Section 6.5.

6.4.6 Summary

Following research into methods of quantitative pitch analysis *Melodyne* appears to provide a reliable method of analysing the recordings of the choirs for this research. Its ability to decompose the sound into voice parts that can then be related directly to the score allows the pitch of notes which have been sung to be quantified. Further, this application has the ability to discern very small pitch differences of individual or small numbers of voices all ostensibly singing the same note. However, while exact pitches within a chord are useful in assessing pitch drift, the analysis of a music performance can and is usually made by the listener. In the case of the choirs in this research it was expected this subjective analysis would be made by the musical directors. It is important to ensure that any pitch drifts quantified in the recordings made for this research are audible in performance for, if inaudible, such findings would lead to a major disparity in the pitch drifts between the quantitative and qualitative methods. The next section discusses how the quantitative measurements of pitch drift may be combined with qualitative results of the same recordings to achieve fair ratings for the pitch drift for each song from each rehearsal. Section 6.6 will then describe how these ratings can be correlated with the attendance of singers at rehearsals – which is one of the variables of interest that changes from rehearsal to rehearsal.

6.5 Matching pitch drift to attendance data

6.5.1 Introduction

Any statistical analyses involving attendance requires the occurrence of pitch drift at a rehearsal performance to be rated in a format to match that of the attendance data, i.e. a 2-state binary format, since any singer can only either be present at a rehearsal or be absent – there are no half measures with this variable (it is assumed all choir members present at a rehearsal will be singing). In her definition of intonation, Latham (2004, p.91) identifies the state of a performer's tuning as being either 'good' or 'poor'. Likewise, Kennedy and Kennedy (2007, p 373) write of a singer's intonation as being either 'good' or 'bad'. Following Latham's lead (being decidedly the more tactful option), the rating of the choirs' pitch drift in rehearsals would be adjudged to be either good ('G') or poor ('P'). It follows therefore that a method for applying these two ratings fairly to the choirs' performances had to be devised. In this section the results from two of the eleven choirs in this research are being used as exemplars. The choirs used are a small vocal group and a chamber choir. These two choirs were chosen simply because their data allowed examples of the techniques used with all the choirs to be clearly demonstrated.

6.5.2 Judging the performance

Performing songs written in four-part harmony, i.e. four independent vocal lines that when sung together form a coherent whole, makes a judgement as to the degree of pitch drift challenging for both qualitative methods (i.e. human ears) and quantitative ones (e.g. *Melodyne's direct note analysis*). It was essential to use at least two methods to give a fair adjudication of any pitch drift found at a rehearsal. Qualitative results for each rehearsal were to be completed by each musical director, as described in sub-Section 6.4.2 and Appendix 10, for use with the quantitative results described in the previous section. The following sub-sections describe these two methods of pitch drift analysis and how they were combined to derive an overall pitch drift rating for each song at every rehearsal of each choir. However, the first stage in determining whether any pitch drift occurred in rehearsals was to extract samples for analysis from the choirs' recordings.

6.5.3 Sampling the rehearsal recordings

The recordings made by the choirs at each rehearsal included two songs plus a given note and/or chord to set the pitch of each song. The choirs were asked to sing both songs consecutively with *Test Piece* being sung first. This ensured consistency between the choirs. There was also a short interval between the two songs to set a new (given) pitch (even if the second song was in the same key). In order to reduce the amount of sound data to a manageable amount, and to aid analysis, each song (including the given note at the beginning of each song) was copied into individual *rehearsal-files*. These files were identified by the title (i.e. *Test Piece* or chosen song), the choir's identification letter and the date of the rehearsal (set automatically by the recorder, described in sub-Section 5.3.2). A digital audio workbench (*Amadeus Pro*® from Hairersoft©, Kenilworth, UK, running on an *Apple iMac* computer) was used to copy the songs from the original rehearsal recordings and create the *rehearsal-files*. Any extraneous audio was removed to ensure anonymity of the recordings and to keep the file sizes manageable. Each file was normalised to a level of –1 dB to ensure similar audio levels without any distortion. The *rehearsal-files* were saved using an uncompressed wave format at a 44.1 kHz sampling rate. However, as mentioned previously, not all the choirs provided a full set of 20 recordings so ultimately a total of 384 *rehearsal-files* were created from 192 rehearsal recordings.

To determine the pitch drift at every rehearsal performance, two suitable chords (notionally the same) were selected from, or near to, the beginning and the end of each song for analysis (sub-Section 6.4.5). Each *rehearsal-file* was opened in *Amadeus Pro* and samples of the chords from within the waveform were copied in turn into *comparison-files* – there being two such files for each choir, one for each song. The two samples were of approximately the same length although in practice the last chord was held for a longer period. The *comparison-files* were pre-recorded with spoken rehearsal numbers, with each number being followed by a short period of silence to allow space for the two samples to be inserted. As an example of preparing a *comparison-file*, Figure 6.16 shows a fragment of *Test Piece* (with the treble G clef set for SATB choirs) displaying the first chord from Bar 2 and the final chord from Bar 17. (The complete score may be viewed in Appendix A8.1) These two chords were selected for comparison as they have, and indeed were designed to have, the same structure.

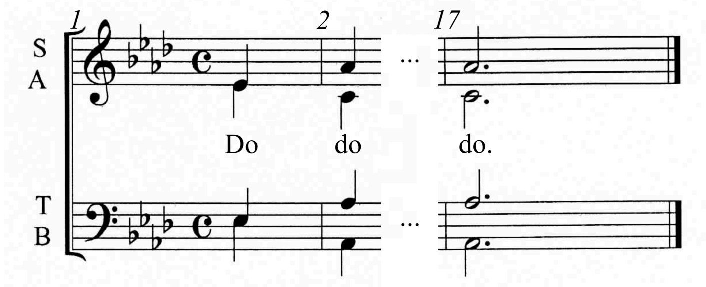


Figure 6.16 A fragment of *Test Piece* set for SATB choirs showing the chords in bars 2 and 17 (with permission). The unison chord in bar 1 would not be suitable

Figure 6.17(a) shows a complete recording of *Test Piece* from the tenth *rehearsal-file* of the set recorded by the small vocal group. A sample of the final chord from the recording (highlighted) is copied into the choir's *comparison-file* for this song. Figure 6.17(b) shows the highlighted chord after being pasted into the *comparison-file* (the first chord has already been copied and pasted into this file). The waveform displayed in front of the two chords represents the word '*Ten*', indicating to the listener that these two chords were taken from the tenth rehearsal.

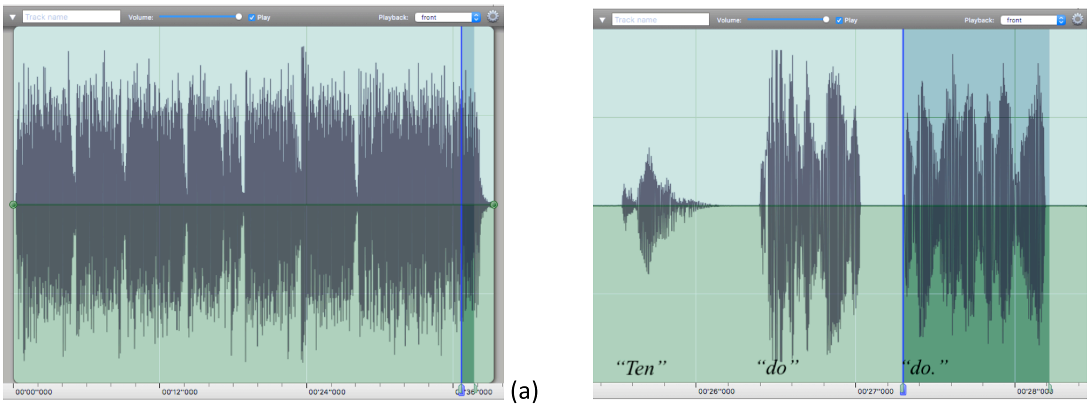


Figure 6.17 (a) Highlighting a sample of the final chord of *Test Piece* taken from the tenth rehearsal of the small vocal group; (b) the sample is pasted into the choir's *comparison-file* for *Test Piece*

The audio CD which accompanies this thesis contains copies of the *comparison-files* for both *Test Piece* and the chosen song for all eleven choirs (Tracks 1–22).

The following two sub-sections discuss how these *comparison-files* were used to rate the pitch drift of the songs taken from each rehearsal using a combination of both qualitative and quantitative analyses.

6.5.4 Quantitative pitch drift analysis of the recordings

The small vocal group example

The results of running *Melodyne's* polyphonic analysis (sub-Section 6.4.5) on the tenth rehearsal of *Test Piece* from the small vocal group's *comparison-file* are shown in Figure 6.18. The two chords (both sung as 'do', and added underneath each chord) can be identified as vertical groups of notes separated by a short period of silence. There is an element of judgement necessary in the selection of notes that comprise the chord. The first note is selected from one of the vocal parts singing the root note A♭. A vertical line is then imagined passing through the remaining vocal parts of the chord. For clarity, in

Figure 6.18(a) the blobs in the chord selected for measurement have been linked in the screenshot with vertical dashed-lines.

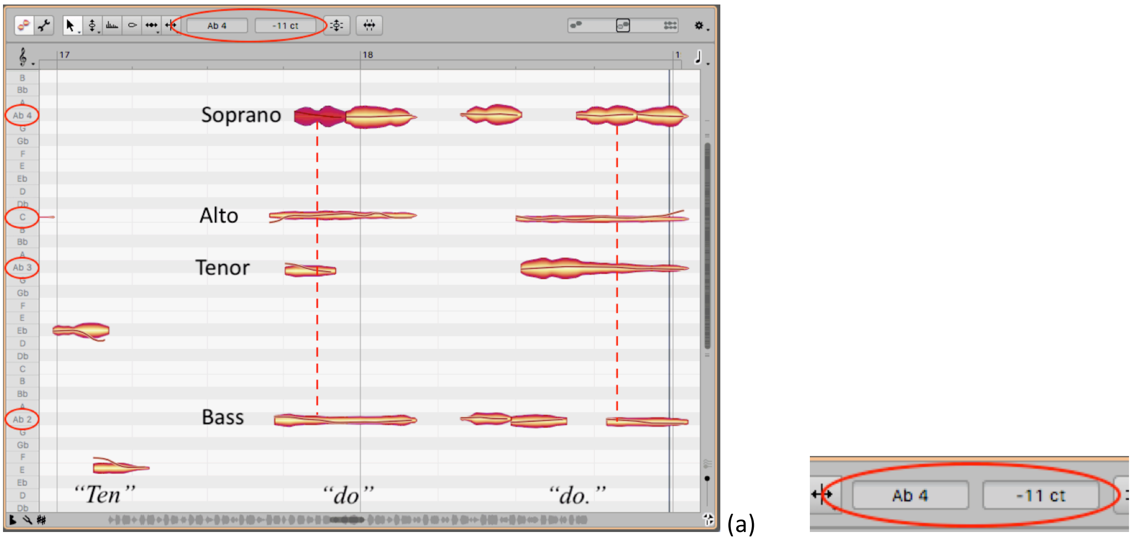


Figure 6.18 (a) A *Melodyne* window showing the decomposition of the two sung chords ('do', 'do'). The four voice parts (SATB) have been added to this window and four the notes ringed to the left of the window; (b) a detail of the sopranos sung note (the blob selected in (a)). The sound file used was that shown in Figure 6.17(b) and was sung by the small vocal group which was selected to demonstrate clearly the methodology used in this research for identifying and measuring note pitches in four-part songs

In this example the soprano, tenor and bass parts are all singing the root note but the sopranos appear to start singing just after the other parts, so the point chosen for analysis had to be moved to include the sopranos. For preference, the section of the sopranos' note immediately following the one highlighted in red should be used as it was better sustained, but measurements at that point would have excluded the tenor part and so this analysis point in the chord had to be rejected. Clicking on any blob (cut by the dashed-lines in Figure 6.18(a) but normally judged using the cursor, visible at the far right) will give the musical note value and any deviation from the ideal equal temperament pitch in cents for the selected blob. The pitch deviation (i.e. the number of cents by which the pitch varies from the note value) for each blob in each part for every rehearsal was transferred to each song's pitch drift data table for each choir. Gaps between blobs in a vocal part, such as those in the final "do" in the soprano and bass lines of Figure 6.18, may be due to there being insufficient audio information in the recording for *Melodyne* to decompose the sound into a note. This is caused by another vocal part masking the sound, or may be the note was not sufficiently sustained by the singers in that part.

The example in Figure 6.18 was chosen because this was a small choir and every member of each vocal part sang very well in unison; this gives a very clear display to aid the description of the quantitative method of judging pitch. When working with larger choirs, judging which points are most appropriate to sample the pitches is more problematic. This is demonstrated in the following sub-section.

The chamber choir example

All the other choirs taking part in this research had many more singers to each part than the small vocal group used as an example in the previous sub-section. Often the analysis of larger choirs showed the singers in a part were not always all singing the same note. Figure 6.19 shows the *Melodyne* display of rehearsal number five taken from the *comparison-file* for *Test Piece*. The example chamber choir, which comprised of more than 16 singers, was singing the same two chords of *Test Piece* as the in the previous example (see Figure 6.16). The *Melodyne* results clearly show that, in this instance, determining the sample point at which to measure the note values for each part of this choir is more problematic. As well as there being pitch inaccuracies in each part from the start, there is also a lack of unison within each voice part, especially with the sopranos where the software has detected five discrete pitches for the first $A\flat_4$ note. This is an example where a number of singers are still settling into the required note – a problem that was noticed with many of the choirs in this research. Interestingly, by the end of the song each part had acquired a better degree of unanimity, albeit with pitch drift. In the case of the first note sampled in the soprano line ($A\flat_4$), the pitch varies from G_4 minus 10 cents to A_4 plus 47 cents, i.e. a range of 257 cents or over two and a half semitones.

The technique adopted in this research for defining the sample points, that was described earlier in relation to the vocal group, has been applied to the screenshot of

Figure 6.19. The two vertical lines show the sample points selected for measurement with the corresponding note values and pitch deviations presented in Table 6.5 (remembering that a negative cent value indicates a flattening of the pitch from the expected equal temperament value). All the note values have been measured and annotated on this screenshot to demonstrate how the pitch varies in each vocal part within a single chord and between the first and last chords of the song.

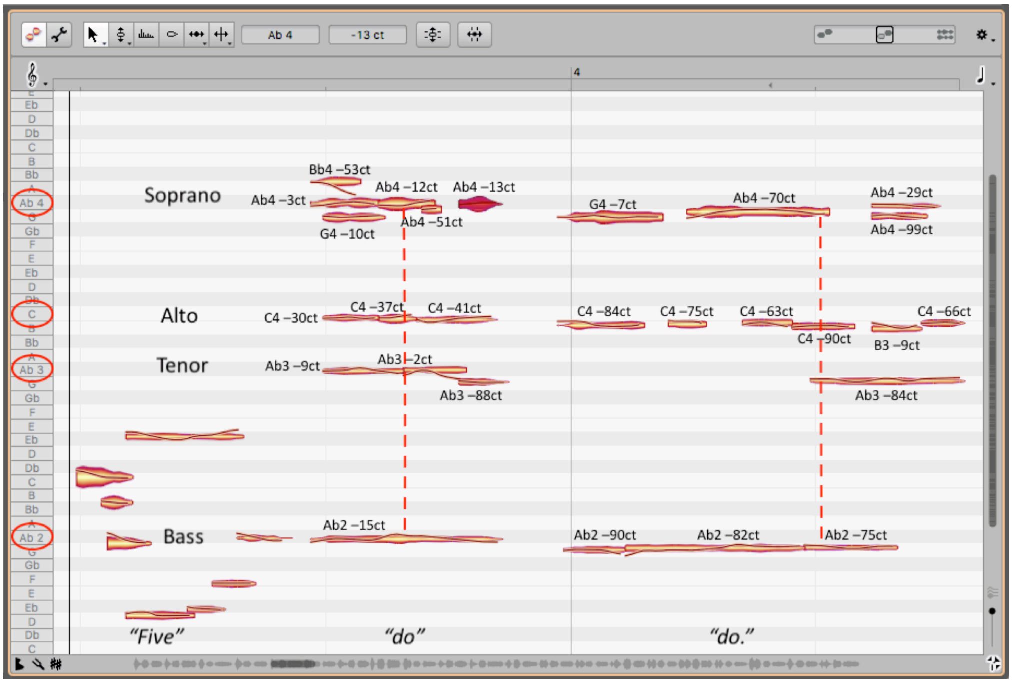


Figure 6.19 *Melodyne*'s results of a recording made at the fifth rehearsal of the example chamber choir – the cluster of five blobs comprising the sopranos' first sung note is typical of a larger amateur choir. The measured note values have been annotated manually to the screenshot

Table 6.5 Note values and pitch deviations for the fifth rehearsal of the example chamber choir at the test points shown by the two vertical lines in Figure 6.19

Vocal part	Note value	Initial measurement point (cents)	End measurement point (cents)
Soprano	$A\flat_4$	–12	–70
Alto	C_4	–37	–90
Tenor	$A\flat_3$	–2	–84
Bass	$A\flat_2$	–15	–75

The pitch drift for each part is obtained simply by subtracting the initial pitch measurement from the end pitch measurement, as shown in Table 6.6. A practical method of rating the quantitative results from each rehearsal was suggested after Ternström and Sundberg (1987). They took the average frequency measurements of the notes sung by six basses over a series of nine chords to determine the degree of unison between them. Following Ternström and Sundberg's method, the four values of pitch drift, one from each vocal part, were averaged to give a pitch drift value, termed mean_R. In this example the average for the fifth rehearsal is –63 cents, as shown in the bottom row of Table 6.6.

Table 6.6 Pitch drift and mean_R calculations for the fifth rehearsal using data taken from Table 6.5 (in grey)

Vocal part	Note value	Initial measurement point (cents)	End measurement point (cents)	Pitch drift (cents)
Soprano	$A\flat_4$	–12	–70	–58
Alto	C_4	–37	–90	–53
Tenor	$A\flat_3$	–2	–84	–82
Bass	$A\flat_2$	–15	–75	–60
mean_R				**–63**

This method of combining pitch drifts by averaging the four parts does raise the question of whether humans also perceive pitch by averaging or whether there are other factors at work. The next sub-section discusses the method by which a set of qualitative results were achieved.

6.5.5 Qualitative pitch analysis of the recordings

The musical directors from each choir were asked for, and agreed to complete, a short questionnaire after each rehearsal (sub-Section 6.4.2). Unfortunately, not all of them completed the forms with sufficient regularity to base a qualitative analysis for each choir on their responses. This problem was not evident until the return of the experiment kit. In retrospect, requesting the musical director from each choir to rate performance and pitch drift at the end of a long rehearsal was too much to ask and the importance of their comments was not made sufficiently clear to them.

As a consequence of this setback a new scheme for qualitative analysis was developed. To achieve fair and reliable results two experienced choral musical directors of amateur choirs were approached to act as adjudicators of pitch drift. At the same time, the assessment methodology was streamlined (the music directors were expected to use a five point scale) by simply rating the pitch drift of each song from every rehearsal as either good (‘G’) or poor (‘P’), as discussed in sub-Section 6.5.1. Subsequently, the individual assessments from the two adjudicators were combined with the quantitative assessment, using an unambiguous *best-of-3* majority voting algorithm to achieve the fairest possible pitch rating for each recording. This assessment method is discussed fully in the next sub-section.

To test the feasibility of the new scheme the two adjudicators, working independently, rated audio examples of pitch drift from just one choir with the aid of appropriate sheet music scores. Their ratings were compared with the quantitative ratings and, on this occasion only, with the ratings from the author. Feedback and discussion took place between the author and each of the adjudicators separately to standardise the awarding of the ratings. Once agreement was reached on standardisation, the two adjudicators were sent anonymised copies of all 22 *comparison-files* plus copies of the sheet music used by the choirs in their performances (with copies of the scores of the chosen songs supplied by the choirs for educational use only in this research).

An example of both adjudicators’ ratings (termed *Qual1* and *Qual2*) of the performances of *Test Piece* over 20 rehearsals for the example chamber choir is shown in Table 6.7. To maintain complete independence, at no time did the adjudicators meet or discuss any of the results.

Table 6.7 The ratings from the two adjudicators of the pitch drift for one choir's performances of *Test Piece* over 20 rehearsals. Rehearsal numbers in blue indicate agreement between the adjudicators

Test Piece																				
Rehearsals	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Qual1 rating	G	G	P	G	P	P	G	G	G	P	P	P	P	P	P	P	P	P	P	G
Qual2 rating	G	G	P	G	P	G	G	G	G	G	G	G	G	P	P	P	P	P	G	G

From Table 6.7 it may be seen there was agreement in 14 of the 20 rehearsals giving 70% agreement which was seen as very satisfactory given the fact that the adjudicators were totally independent and assessing pitch drift involves some very personal judgements. So what of those rehearsals where there was no agreement? This is when the inclusion of the third (quantitative) rating ensures that the overall pitch drift rating result for each rehearsal is as fair as possible. The method of reconciliation is considered in the next sub-section.

6.5.6 Reconciling the two data sets from the recordings

For the quantitative results obtained from *Melodyne* to be used beside the two binary qualitative results to achieve an overall pitch drift rating for each rehearsal, the three data sets must be reconciled. In order to derive a binary result for each rehearsal from the quantitative data the first step was to arrive at an average value representing each choir's own standard of pitch drift, termed mean_{ALL}. This was necessary because each choir needed to be judged on its own degree of pitch drift, not set against all the other choirs by using an arbitrary standard such as 50 cents. For each choir two values of mean_{ALL} (one for each song) were calculated by averaging the pitch drifts of all four voice parts (mean_{R}) from all the rehearsals. A binary pitch drift rating for each song in a rehearsal could be determined by comparing the pitch drift from each rehearsal (mean_{R}) against the choir's overall average pitch drift (mean_{ALL}). It must be stressed that this was not a way of comparing pitch drifts with any other choirs or standards. It is also important to be aware that in using this method the mean_{ALL} value is very likely to be different for each song as well as for each choir.

To achieve a binary result the value of mean_{R} from each rehearsal was tested against mean_{ALL}. If mean_{R} was less than mean_{ALL} a good ('G') rating was awarded as the pitch drift was less than the average for the choir at that rehearsal. A poor (‘P’) rating was given if mean_R was equal to or above mean_{ALL}. For choirs who experienced very little pitch drift a minimum value for mean_{ALL} was set at ±14 cents after Ternström (1993), who reported that ten listeners with extensive conducting and/or singing experience would *tolerate* [his italics] a deviation from the f_0 of ±14 cents. Applying this procedure to the data from the example chamber choir used in the previous sub-section, the value of mean_{ALL} for *Test Piece* was found to be –38 cents. The quantitative pitch drift rating (termed *Quant* rating) was calculated from mean_R for each rehearsal and is shown in row three of Table 6.8.

Table 6.8 Adjudication of *Quant ratings* by comparing mean_R against mean_{ALL} (note that mean_R for rehearsal 5 is –63 cents as shown in Table 6.6)

Test Piece																					
Rehearsals	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	mean_{ALL}
mean_R	-19	-32	-43	-20	-63	-33	-66	-33	-7	-5	-27	-46	-40	-70	-70	-32	-25	-67	-41	-26	-38
Quant rating	G	G	P	G	P	G	P	G	G	G	G	P	P	P	P	G	G	P	P	G	

6.5.7 Determining pitch drift ratings for each rehearsal

The pitch drift ratings at rehearsals of each choir’s performance for each song is determined by applying a *best-of-3* majority voting algorithm to the three ratings *Qual1, Qual2 and Quant*. The data taken from Tables 6.7 and 6.8 respectively determine the binary pitch drift ratings for each rehearsal performance shown in the bottom row in Table 6.9 for the example chamber choir singing *Test Piece*.

Table 6.9 Determining the pitch drift ratings for the example chamber choir at rehearsals of *Test Piece*

Test Piece																				
Rehearsals	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Quant rating	G	G	P	G	P	G	P	G	G	G	G	P	P	P	P	G	G	P	P	G
Qual1 rating	G	G	P	G	P	P	G	G	G	P	P	P	P	P	P	P	P	P	P	G
Qual2 rating	G	G	P	G	P	G	G	G	G	G	G	G	G	P	P	P	P	P	G	G
Pitch drift rating	G	G	P	G	P	G	G	G	G	G	G	P	P	P	P	P	P	P	P	G

Considering the pitch drift ratings for this example chamber choir’s *Test Piece*, shown in Table 6.9, the eleven rehearsal numbers highlighted in yellow indicate unanimous agreement for all three ratings, *Quant*, *Qual1* and *Qual2*. Those highlighted in blue and white are determined using the *best-of-3* majority voting algorithm. In the case of the three rehearsals highlighted in blue there was agreement between the two *Qual* ratings (i.e. both adjudicators). For the remaining six rehearsals highlighted in white the overall ratings were obtained from agreement with the *Quant* rating and one or other of the *Qual* ratings. The ratings for the chosen song from the same choir are shown in Table 6.10. This demonstrates that there is a greater agreement between the three ratings than for *Test Piece*.

Table 6.10 Determining the pitch drift ratings for the example chamber choir at rehearsals of chosen song

chosen song																				
Rehearsal	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Quant rating	G	G	P	G	P	G	P	P	G	P	G	P	G	P	P	P	P	G	P	G
Qual1 rating	G	G	G	G	P	G	P	G	P	P	G	P	G	P	G	P	P	G	P	P
Qual 2 rating	G	P	P	G	P	P	P	P	P	P	G	P	G	P	G	P	P	G	P	G
Pitch drift rating	G	G	P	G	P	G	P	P	P	P	G	P	G	P	G	P	P	G	P	G

An analysis of the pitch drift rating agreements, as opposed to the disagreements, for each of the two songs performed by this example chamber choir is shown in Table 6.11. Tables showing the pitch drift ratings of both songs for all eleven choirs are shown in Appendix 14.

Table 6.11 Percentage agreement of the three pitch drift ratings for each song for one choir over 20 rehearsals taken from Tables 6.9 and 6.10

Rating results agreement for one choir	*Test Piece*	Chosen song	Average
Unanimous	55%	65%	60%
Between adjudicators (*Qual1* and *Qual2*)	70%	80%	75%
Between *Melodyne (Quant)* and one adjudicator (*Qual*)	85%	90%	88%

An analysis of the pitch drift rating agreements, as opposed to the disagreements, of both songs combining all choirs for all 192 rehearsals is shown in Table 6.12.

Taking both songs into consideration across all choirs there was unanimous agreement in 66% of the rehearsals. The two adjudicators were in agreement in 76% of the rehearsals. However, one or other of the adjudicators agreed with the quantitative ratings in 91% of the cases. Again, the chosen song ratings appear to offer a slightly greater unanimity than the ratings for *Test Piece*. On average choirs took only 43 seconds to sing *Test Piece* whereas the chosen songs were longer taking between 70 seconds and 200 seconds to perform. On reflection, *Test Piece* could have been longer, or taken more slowly, or possibly sung twice to allow for pitches to settle, which may have assisted the adjudication process. This will be discussed further in Chapter 7.

Table 6.12 Percentage agreement of the three pitch drift ratings for each song for all choirs (192 rehearsals)

Rating results agreement for all choirs	***Test Piece***	**Chosen song**	**Average**
Unanimous	58%	74%	66%
Between adjudicators (*Qual1* and *Qual2*)	72%	80%	76%
Between *Melodyne (Quant)* and one adjudicator (*Qual1 or 2*)	87%	94%	91%

Where a difference occurred in the results between the two adjudicators, the *Quant* ratings were rechecked to ensure no error had occurred in the measurements of the pitch drift in any of the vocal parts. If no obvious reasons were found then the difference could be in identifying which part within the chord had affected the pitch. The adjudicators assessed the difference in the overall sound between the two chords and sometimes may have homed in on a particular part when determining their pitch drift rating whereas the quantitative method took the average of the pitches of the four notes to provide the rating. Judgement of pitch drift was made even more difficult for the adjudicators where the chosen song contained a key change making the last chord completely different from the first one. Unfortunately, a song without a key change was not specified when choirs chose their song. However, the only song with a key change was chosen by both Barbershop choruses, which was fortunate.

6.5.8 Comparing the pitch drift ratings of the choirs

The good pitch drift ratings, averaged across rehearsals for all the choirs for both songs, are given in the bar chart of Figure 6.20. The coloured patterns in the bars represent the different songs. The first bar for each choir (orange diagonals) represents *Test Piece* (sung by all choirs). The second bar represents the chosen song with each colour and pattern representing a different song – e.g. blue crosshatching indicates that choirs A, E, F and H all sang the same chosen song – and are grouped together for ease of comparison.

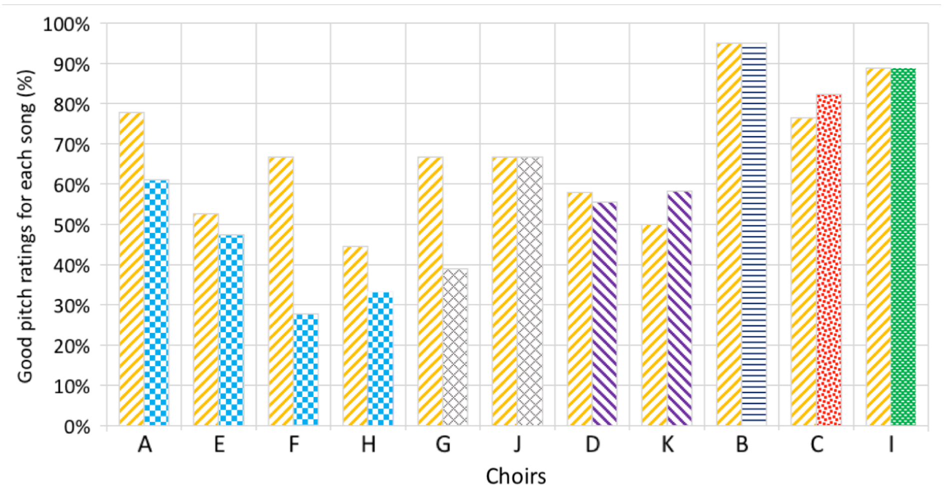


Figure 6.20 Good pitch drift ratings for both songs from each choir (grouped by chosen song)

From Figure 6.20 it can be seen that all the choirs demonstrate some degree of pitch drift when singing the same two songs over a period of up to 20 rehearsals. Choirs B and I produced good pitch drift ratings on over 85% of the occasions when they rehearsed the songs, with Choir B exhibiting the least drift in pitch of any choir taking part in these experiments. Conversely, Choirs F and H only achieved 30% of good pitch drift ratings for their chosen song (incidentally, the same song) but along with most other choirs performed better in *Test Piece*. The average good pitch drift rating for both songs from all the choirs was 64%. This outcome, that choirs experience pitch drift when singing *a cappella* music, was not unexpected given the findings of the academic publications presented in the literature review in Chapter 3. This was further supported by the survey responses of choral practitioners and the outcomes of the interviews and correspondence presented in Chapter 4.

However, this research set out to investigate why this pitch drift is irregular at different rehearsals, as demonstrated by the pitch drift ratings for the example chamber choir in Tables 6.9 and 6.10. This is further demonstrated by Figure 6.21 which compares Choirs B and H not just for irregularity in drift but also the way in which directions of the drift differs.

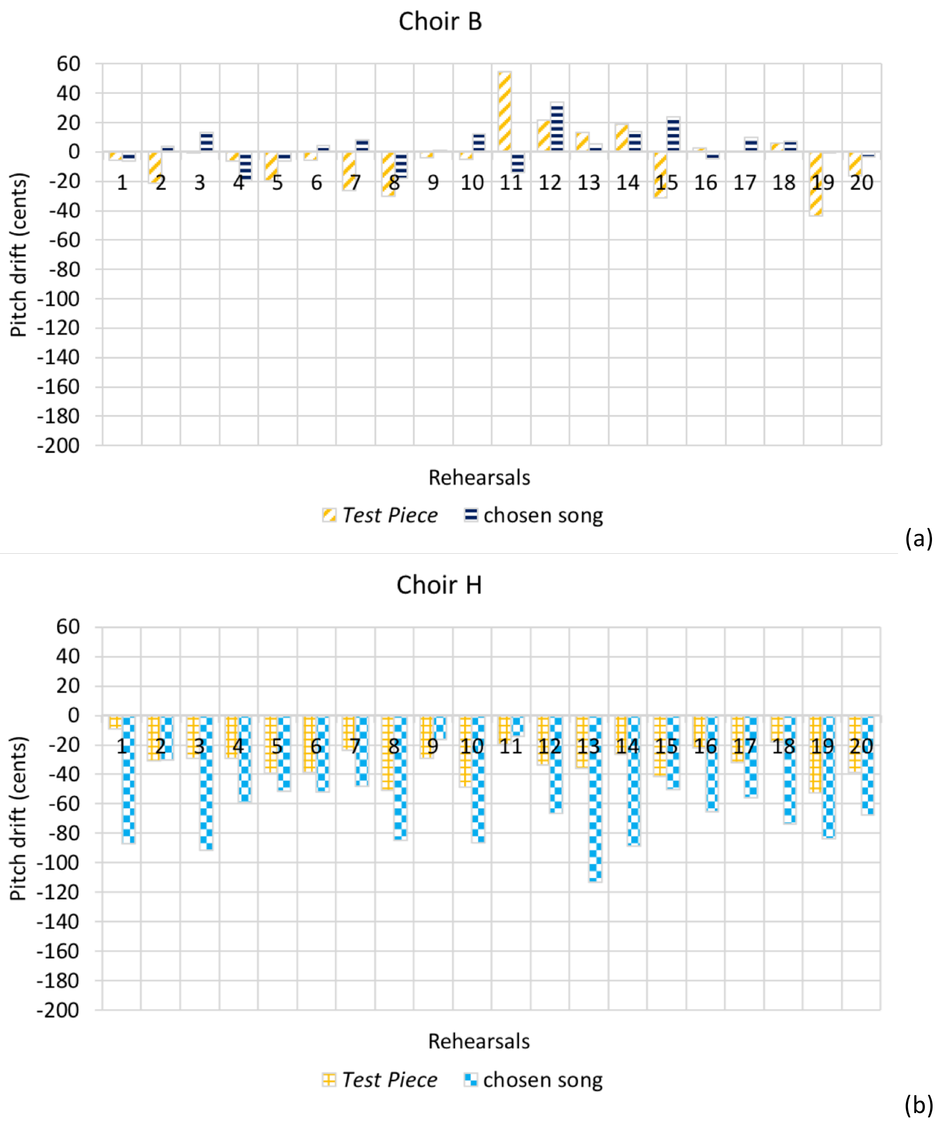


Figure 6.21 Quantitative results for pitch drift of both songs at each rehearsal: (a) for Choir B; (b) for Choir H. Results for all choirs may be found in Appendix 15

For these two charts the quantitative measurements of pitch drift, which give the direction of the pitch drift as well as the value in cents, have been used. Individual charts for all of the choirs may be found in Appendix 15.

Choir B's results (Figure 6.21(a)) demonstrate the pitch drifting irregularly at each rehearsal, by going sharp on some occasions and flat on others. Thus, their overall average for both songs at all rehearsals is merely –1 cent. Although both songs have similar average pitch drift ratings (see Figure 6.20) the standard deviation (SD) for performing *Test Piece* is 22 cents whereas for the chosen song it is only 13 cents. This may be because the singers felt more confident performing a piece from their repertoire rather than the new *Test Piece*.

The results for Choir H (Figure 6.21(b)) shows that they too drifted irregularly at each rehearsal but their pitch was consistently flat with an overall average of –59 cents. This choir maintained pitch better in *Test Piece* (SD = 19 cents) than their chosen song (SD = 39 cents). Table 6.13 shows the number of occasions (as a percentage) when the pitch drifted down for both *Test Piece* and the chosen song for all the choirs along with their overall pitch drift averages.

Table 6.13 Occasions when pitch drifted flat in rehearsals for each song for all choirs expressed as percent plus the average pitch drift for both songs combined

Choir	Pitch drift flat in rehearsal		Average pitch drift for both songs	Number of singers
	***Test Piece* (%)**	**chosen song (%)**		
A	61	100	–22	26
B	60	35	–1	25
C	70	18	1	23
D	100	100	–69	26
E	100	100	–69	34
F	100	100	–59	21
G	100	100	–47	71
H	100	100	–48	25
I	33	44	1	8
J	67	100	–30	26
K	100	100	–78	22

Although five choirs experienced occasional sharpening of pitch in *Test Piece* only three (B, C and I) experienced sharpening in their chosen song as well, which brought their mean pitch drifts close to zero. The remaining choirs drifted flat in their chosen songs leading to average pitch drifts of between –22 and –78 cents. There may be a possible link between the choirs that drifted to a lesser degree at their rehearsals tending to drift irregularly both sharp and flat and those choirs that experienced greater degrees of pitch drift always drifting flat. This interesting result may be associated with attendance patterns of singers which is the subject of Section 6.6.

6.5.9 The effect of choir numbers on pitch drift

Regression analysis can be used to determine whether a statistically significant relationship (correlation) exists between the occurrence of pitch drift, termed the dependent variable, and any variables associated with or acting on the choir, termed the independent variables. Here, the independent variable is the size of the choir which is analogous to the number of singers present at the rehearsals. The regression data analysis tool in *Excel 2016®* returns the *coefficient of determination* (R^2) and the *analysis of variance* (*ANOVA*) which includes the *probability* (p-value) of a relationship between the two variables. The value of R^2 is used as a predictor when testing hypotheses, with values approaching one indicating a close linear relationship between the variables. Values of R^2 well under one may be due to confounding variables or other factors which may affect both the dependent and independent variables. However, it is the p-value that determines whether the *null hypothesis* (H_0), in this case that choir numbers have no significant effect on pitch drift, can be rejected. This is discussed more fully in Section 6.6.6. Note that throughout this thesis the initial level set for the p-value to be significant is at, or under, 0.05 (5%).

The results of running a regression analysis on the mean pitch drift of each choir against choir numbers is shown in Figure 6.22. An R^2 value of 0.07 shows that no linear relationship exists and a *p*-value of 0.431 means H_0 cannot be rejected. Thus, there is no correlation between the mean pitch drift of the choirs and the number of singers in each choir for this cohort of choirs.

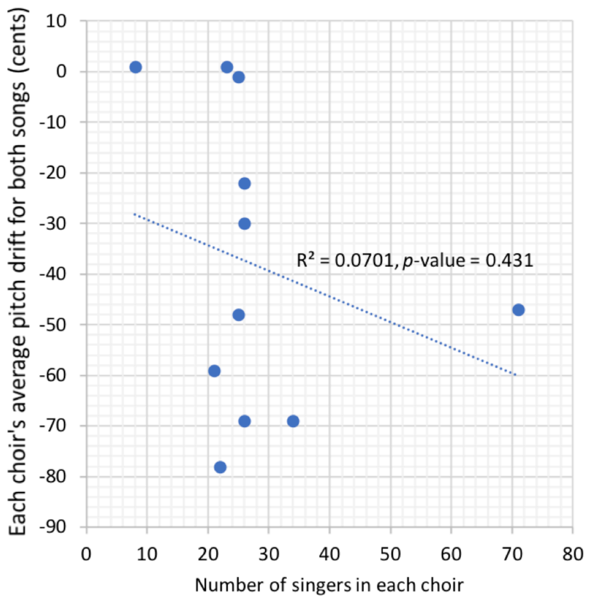


Figure 6.22 No correlation exists between the mean pitch drift and the number of singers in each choir (total = 11)

6.5.10 Summary

The charts in Appendix 15, along with the recordings of the choirs' rehearsals, confirm that pitch drifts irregularly from rehearsal to rehearsal for all the choirs in this research. However, when averaged over all their rehearsals, three choirs exhibited very low values of mean pitch drift due to their pitch drifting both sharp and flat, whereas six choirs only ever drifted flat which gave then larger values of mean pitch drift. There was no significant correlation between the size of the choir and its average pitch drift.

The next step is to consider whether one or more of the variables (attendance and environment) to which the choirs were subjected from rehearsal to rehearsal had any significant effect on the differences in pitch drift. The attendance of singers at rehearsals is the first to be considered.

6.6 Attendance and pitch drift

6.6.1 Introduction

This section determines whether there is any correlation between the attendance of any particular singer at a rehearsal and the pitch drift rating at that rehearsal. It is quite possible for individual singers to initiate a drift in pitch which may be taken up by others both in the same vocal part and by the choir as a whole. Of course, this means the pitch is better maintained or made worse depending on the effect of the singer. This section, which takes examples from a Barbershop chorus, starts by discussing the attendance pattern of singers.

6.6.2 Rehearsal attendance data

All the choirs registered the attendance of singers at each rehearsal. Each choir was asked to provide copies of this data which was anonymised, if not already the case, before use. Attendance is in a two-state (binary) quantity which was standardised for this research with a ‘1’ being allocated for singers attending rehearsals and ‘0’ allocated for singers missing rehearsals. The attendance pattern of three singers from the example Barbershop chorus, along with the total attendance at each rehearsal, is shown in Table 6.14.

Table 6.14 A fragment of the attendance register for three singers (presence is indicated in blue-grey, absence in light-yellow). The total attendance at each rehearsal is shown in the bottom row

Rehearsal	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Singer A	1	0	1	1	1	1	0	0	1	1	1	1	1	1	0	1	0	0	0	0
Singer B	0	1	1	1	0	1	1	1	1	1	1	0	0	1	0	1	1	1	1	1
Singer C	0	1	1	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	0	1
Attendance	17	20	17	15	16	20	13	17	20	15	14	13	15	19	13	11	12	12	17	16

Pearson's chi-squared tests, applied to the results from contingency tables, are used to determine the probability that the pitch drift at a rehearsal might be influenced by the attendance pattern of any of the singers. The following sub-section introduces contingency table methodology.

6.6.3 Methodology used to determine relationships

The methodology used to determine whether a relationship exists between pitch drift and attendance starts with pairs of contingency tables, both of a 2 x 2 matrix format, to compare the frequency distributions of these two variables. Pitch drift ratings and attendance and may be compared directly as they have the same binary properties, the latter having been developed earlier in sub-Section 6.5.7. There are two pairs of contingency tables assigned to each singer, one pair for each song, as the pitch drift ratings for each song are treated independently. The first table in the pair, known as the *observed* contingency table, shows the actual frequency distribution of the singer's pattern of attendance and the actual pitch drift good ('G') and poor ('P') ratings at the rehearsals attended and missed. The second, known as the *expected* contingency table, again shows the frequency distribution of the singer's pattern of attendance but in this case having no effect on the pitch drift, the pitch drift results being distributed in the overall 'G' to 'P' ratio for the choir. Any correlation between these two tables may be found using appropriate statistical tests, in this case *Pearson's chi-squared* test.

6.6.4 Setting up contingency tables

Two sets of contingency tables – the *observed* table and the *expected* table – are needed for each singer, one set for each song per choir. The contingency tables consist of 2×2 matrices with the attendance data in rows and pitch drift ratings in columns. The *observed* contingency table comprises of the number of rehearsals attended or missed (present = '1', absent = '0') for that singer set against the number of 'G' and 'P' pitch drift ratings over all rehearsals, giving four values in total. The *expected* contingency table uses the same attendance data but assumes that the pitch drift ratings were distributed in the overall 'G' to 'P' ratio for the choir, which would be the case if a singer's presence or absence had no effect on the pitch drift. Again, this results in a table with four values. Figure 6.23 shows the generic form of the 2×2 contingency table used here. The extra row and columns are for checksums which must equal the total number of rehearsals.

Table type	**Pitch drift**		
Attendance	**'G'**	**'P'**	**Checksum$_{Col}$**
Present	number of rehearsals the singer was present, and the pitch drift rating was good	number of rehearsals the singer was present, and the pitch drift rating was poor	row sum
Absent	number of rehearsals the singer was absent, and the pitch drift rating was good	number of rehearsals the singer was absent, and the pitch drift rating was poor	row sum
Checksum$_{Row}$	column sum	column sum	total number of rehearsals

Figure 6.23 A generic form of a 2×2 matrix contingency table with checksum row and columns added to check for errors (the data entered in the rows and columns should both equal the total number of rehearsals)

In the following example, the data used to construct the two sets of contingency tables are for Singer T. This singer's attendance data is shown in Table 6.15, a '1' indicating present (highlighted with blue-grey) and '0' indicating absent (highlighted in light-yellow, matched against the pitch drift ratings for the chosen song of the example chorus. There are 10 rehearsals with 'G' pitch drift ratings (highlighted in light-green) and 10 with 'P' pitch drift ratings (highlighted in light-red). This is the pitch drift ratio for this choir.

Table 6.15 Attendance pattern for one singer against the pitch drift rating for the chosen song at each rehearsal

Rehearsal	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Singer T	1	1	0	0	0	1	1	1	1	0	0	0	1	1	0	0	1	1	1	1
Pitch drift rating	G	G	G	P	P	P	P	P	G	G	G	P	G	G	G	G	P	P	P	P

Building an observed contingency table

Using the data from Table 6.15, the *observed* contingency table is a summary of Singer T's attendance and the choir's pitch drift ratings. To see exactly how the contingency table is constructed, consider the first rehearsal in this table. At this rehearsal Singer T was present and the choir's pitch-drift rating was 'G' so a count of one is added to the appropriate cell of the 2×2 matrix shown below:

Observed – T	**Pitch drift**	
Attendance	**'G'**	**'P'**
Present	1	
Absent		

Singer T was also present at four more rehearsals when the choir's pitch drift was also rated 'G': 2, 9, 13 and 14. Including rehearsal 1, this gives a total count of five rehearsals at which this singer was present and when the pitch-drift rating was 'G', as summarized below:

Observed – T	**Pitch drift**	
Attendance	**'G'**	**'P'**
Present	5	
Absent		

If the rehearsals when the singer was present, and the pitch was rated 'P' are now considered, i.e. rehearsals 6, 7, 8, 17, 18, 19 and 20, then a total count of 7 rehearsals is added to the table under the 'P' column:

Observed – T	**Pitch drift**	
Attendance	**'G'**	**'P'**
Present	5	7
Absent		

Turning to the rehearsals when the singer was absent, there were 5 rehearsals where the singer was absent, and the pitch was rated as 'G', i.e. rehearsals 3, 10, 11, 15 and 16, so the table is updated with a count of 5 as shown:

Observed – T	Pitch drift	
Attendance	**'G'**	**'P'**
Present	5	7
Absent	5	

Finally, there were 3 rehearsals where the singer was absent and the pitch was rated as 'P', i.e. rehearsals 4, 5 and 12, so the table is completed by adding a count of 3 for these rehearsals:

Observed – T	Pitch drift	
Attendance	**'G'**	**'P'**
Present	5	7
Absent	5	3

Finally, a checksum row and column are added to the table. If the table has been completed correctly, the sum of the rows and columns will each give the total number of the choir's rehearsals in the bottom right-hand corner. This value must agree with the number of rehearsals in Table 6.15. The completed *observed* contingency table shown below as described in Figure 6.23:

Observed – T	Pitch drift		
Attendance	**'G'**	**'P'**	**$\text{Checksum}_{\text{Col}}$**
Present	5	7	12
Absent	5	3	8
$\text{Checksum}_{\text{Row}}$	10	10	20

Building an expected contingency table

The *expected* contingency table has the same format as the *observed* contingency table. That is, it contains a 2×2 matrix relating presence or absence of the individual singer to pitch drift rating. However, the *expected* contingency table assumes that the presence or absence of the singer has no bearing on the observed pitch drift rating. Thus, it is possible to define a 'G' ratio as the rehearsals with a good rating divided by the total number of rehearsals with the remainder being rated as poor 'P', which for the example choir used above is 10/20 = 0.5. This is because for this particular choir there were 10 rehearsals with good pitch drift ratings and 10 with poor ones. Looking back at the completed *observed* contingency table on the previous page, it can be seen that Singer T in this choir was present on 12 occasions. Thus, if a singer's presence had no effect on pitch-drift, we might expect 12 x 0.5 = 6 of these 12 occasions to be rated 'G' and 12 – 6 = 6 to be rated 'P' as the good ratio for this choir is 0.5. Similarly, a 'P' ratio can be defined as the rehearsals with a poor rating divided by the total number of rehearsals, which for this choir is 10/20 = 0.5 (or 1 minus the 'G' ratio). On the 8 occasions when the singer was absent, we might expect the pitch-drift rating to be 'G' on 8 x 0.5 = 4 occasions and 'P' on 8 – 4 = 4. Note that the 'G' and 'P' ratios happen to be the same in this case as there were an equal number of good and poor rehearsals, but this would not always be the case. This gives the completed *expected* contingency table below for Singer T in the example choir:

Expected – T	**Pitch drift**		
Attendance	**'G'**	**'P'**	**$\text{Checksum}_{\text{Col}}$**
Present	6	6	12
Absent	4	4	8
$\text{Checksum}_{\text{Row}}$	10	10	20

Comparing the completed *observed* and *expected* contingency tables, reproduced below, it may be seen that the counts for present and absent differ, but all the checksum rows and columns are the same. Although this example had equal numbers of good and poor ratings contingency tables work with any number of rehearsals and for any ratios of good to poor ratings.

Observed contingency table for Singer T:

Observed – T	**Pitch drift**		
Attendance	**'G'**	**'P'**	**$\text{Checksum}_{\text{Col}}$**
Present	5	7	12
Absent	5	3	8
$\text{Checksum}_{\text{Row}}$	10	10	20

Expected contingency table for Singer T:

Expected – T	**Pitch drift**		
Attendance	**'G'**	**'P'**	**$\text{Checksum}_{\text{Col}}$**
Present	6	6	12
Absent	4	4	8
$\text{Checksum}_{\text{Row}}$	10	10	20

Having produced the observed and expected contingency tables it is necessary to apply *Pearson's chi-squared test* to determine whether any correlation exists between the two contingency tables.

6.6.5 Determining whether attendance affects pitch

On completion of the two contingency tables for each singer in the choir, following the procedure for the chosen song described in the previous sub-section, *Pearson's chi-squared* (χ^2) *test* may be used to determine whether each singer's *observed* data is independent of the *expected* data for their distribution of attendance and absence at rehearsals. The χ^2 value for each singer is then used to determine whether any singers have a significant effect on the pitch drift or not when the choir is performing their chosen song. This procedure is then repeated using the pitch drift results when the choir was performing *Test Piece*.

Pearson's chi-squared test, shown in Equation 6.1, takes the values from corresponding cells in the *observed* and *expected* contingency tables and calculates χ^2. The values of χ^2 are entered into the corresponding cells within a new 2×2 table. The four values are then summed to obtain a cumulative $\chi^2{}_{\text{COM}}$ result for each singer. This result is used, along with the degrees of freedom, found from Equation 6.2, in the *Excel* function of Equation 6.3 to calculate a probability (*p*-value) for each singer for the rehearsal performances of the chosen song. The *p*-value determines whether the singer is likely to have a significant effect on the pitch drift or not.

$$\chi^2 = \sum_{i=1}^{n} \frac{(observed\ \text{data}_i - expected\ \text{data}_i)^2}{expected\ \text{data}_i} \qquad 6.1$$

where *n* = the number of data cells in the contingency table (here n = 4) and *DF* is the degrees of freedom, as shown in Equation 6.2. Degrees of feedom is used as a multiplier when calculating the probability (*p*-value) in Equation 6.3 below.

To calculate χ^2 using the values taken from Singer T's contingency tables for the chosen song derived above, Equation 6.1 is completed as follows. The value in the top left cell of the *expected* contingency table (value = 6) is subtracted from the value in the top left cell of the *observed* contingency table (value = 5) and then squared giving $(5 - 6)^2$ which equals 1 (following procedure in the numerator of Equation 6.1). This result is then divided by the value in the top left cell of the *expected* contingency table giving (1/6) which equals 0.167. This value is entered in the top left cell of the new table and the process repeated for the three other cells to complete the table as shown below:

Singer T	**Pitch drift**	
Attendance	**'G'**	**'P'**
Present	0.167	0.167
Absent	0.250	0.250

Thus χ^2_{COM} is the sum of the 4 states of the table (*n*) which gives:

$$\chi^2_{\text{COM}} = (0.167 + 0.167 + 0.250 + 0.250) = 0.833$$

The *Degrees of freedom* (DF) value which is necessary for use in Equation 6.3 below is calculated in Equation 6.2:

$$DF = (r - 1)\times(c - 1) \qquad 6.2$$

where r = number of rows and c = number of columns in the contingency tables. Here both are equal to 2 so *DF* becomes (2 – 1) × (2 – 1) which equals 1.

Once the value of χ^2_{COM} and *DF* are found they are used to determine whether the result for this singer is statistically significant or not. This is achieved using the *cumulative* *distribution function*, which is realised in *Excel's* CHISQ.DIST worksheet function shown in Equation 6.3. This returns a probability (*p*-value) for this singer.

$$\text{Probability } (p\text{-value}) = (1 - \mathrm{CHISQ.DIST}\{0.833{,}1{,}1\}) = 0.361 \qquad 6.3$$

where CHISQ.DIST takes the three parameters shown: χ^2_{com}, *degrees of freedom* (= 1), and *cumulative distribution function* (= True (1)).

The degrees of freedom is set to 1 (from Equation 6.2) and the *cumulative* argument is set to True (= 1), which selects the cumulative distribution characteristics. Applying Equation 6.3 in an *Excel* worksheet gives a *p*-value for Singer T of 0.361 for all the rehearsal performances of the choir's chosen song.

An indication of the kind of effect a singer may be having on the pitch drift at rehearsals may be discovered by subtracting the top left *expected* value from the top left *observed* value of the contingency tables for each singer's songs (basically the numerator of Equation 6.1 without squaring the result). This value is here termed the *G/P rating*; a positive result indicating this singer was more likely to be present at rehearsals when the pitch drift was rated as good, a negative result indicating the opposite, i.e. the pitch drift was rated as poor when this singer attended rehearsals. In the example here subtracting the top left *expected* value of 6 from the top left *observed* value of 5 gives (5 – 6) which equals –1. This indicates the singer was more likely to be present at rehearsals when the pitch drift was rated as poor.

These statistical methods above are applied to all the singers other than those with full attendance (100%) to obtain a set of probability scores. The reason why full attendance cannot be tested is that the *observed* and *expected* values are equal and therefore cancel out. Hence, this procedure may only be applied to singers who do not attend all of the rehearsals. Of course, if all singers attended every rehearsal attendance could not be considered as a cause of pitch drift.

The following sub-section presents the probability scores calculated for all the singers in the choir of Singer T. The tables of results for all choirs are available in Appendix 16.

6.6.6 Identifying singers affecting pitch drift

For any singer there is a possibility that any apparent correlation between the choir's pitch drift for either song is due purely to chance. The smaller the *p*-value for the singer the more improbable it becomes that the difference in the contingency tables, described above, arises by chance and therefore the more likely the singer is a contributory factor to the degree of pitch drift.

For each of the songs shown in Table 6.16 the default position, known as the null hypothesis (H_0), is that there is no correlation between the singers' attendance and pitch drift. H_0 cannot be rejected unless the alternative hypothesis (H_1), can be proven. Thus, H_0 can only be rejected if a singer's *p*-value is significant, and for this to be the case the arbitrary but conventional value of 0.05 (i.e. 5%) or under is used. The colour-coding scheme of Table 6.16 makes significant singers more obvious.

Considering the columns of singers' *p*-values for *Test Piece* and the chosen song, the results in dark red identify *p*-values of or below 0.05 that can be considered significant, thus rejecting H_0. Those results above 0.05, i.e. light red, orange, yellow and green, do not meet the significance criterion. In these cases H_0 cannot be rejected; that is, we cannot reject the hypothesis that chance accounts for the apparent relationship between the singer's attendance and pitch drift. The values in the *G/P rating* column are also coded for ease of identification with light-green indicating a positive value and pink a negative value. The relevance of these values was explained in the previous sub-section.

Table 6.16 Probability values for the data analysis of each singer's attendance against pitch drift for all of the singers in Singer T's choir (note there are only 25 singers listed as Singer M had 100% attendance and has been omitted). The colour-codes are explained in the accompanying text

	Test Piece		chosen song		
Choir D	***p*-value T**	**G/P rating**	***p*-value C**	**G/P rating**	**Attendance**
Singer A	0.028	2.400	0.068	2.000	60%
Singer B	0.795	-0.250	0.606	-0.500	75%
Singer C	0.194	-1.250	0.606	-0.500	75%
Singer D	0.391	0.950	0.653	-0.500	55%
Singer E	0.178	-1.500	0.074	-2.000	50%
Singer F	0.436	0.750	0.606	0.500	75%
Singer G	0.257	0.550	0.305	0.500	95%
Singer H	0.391	0.950	0.178	1.500	55%
Singer I	0.142	-1.600	0.068	-2.000	60%
Singer J	0.257	-0.550	0.305	-0.500	5%
Singer K	0.660	-0.350	0.531	-0.500	85%
Singer L	0.353	-0.450	0.305	-0.500	95%
Singer N	0.089	1.350	0.060	1.500	15%
Singer O	0.369	-0.800	1.000	0.000	80%
Singer P	0.413	0.650	0.531	0.500	85%
Singer Q	0.028	2.400	0.006	3.000	60%
Singer R	0.279	1.150	0.639	0.500	35%
Singer S	0.660	0.350	0.531	0.500	15%
Singer T	0.582	-0.600	0.361	-1.000	60%
Singer U	0.964	0.050	0.653	-0.500	45%
Singer V	0.391	0.950	0.178	1.500	55%
Singer W	0.142	1.600	0.361	1.000	40%
Singer X	0.069	1.750	0.606	0.500	75%
Singer Y	0.795	-0.250	0.121	-1.500	75%
Singer Z	0.582	0.600	0.361	1.000	40%

Referring to the *Test Piece* p-value column of Table 6.16, Singers A and Q are of significance. However, taking any single p-value as significant is open to question as this result may be due to chance. The probability of observing at least one significant result due to chance is given by Equation 6.4:

$$\text{Probability} = (1 - \text{probability of no significant results}) \qquad 6.4$$

where the probability of no significant results is $(1 - \text{chosen significance level})^{\textit{number of hypotheses} \text{ to test}}$

In this case the chosen significance level is 0.05 and the *number of hypotheses* is 25 as there are 25 singers in this example choir. Thus:

$$\text{Probability of one significant result due to chance} = \left(1 - (1 - 0 \cdot 05)^{25}\right) \approx 0.72 \text{ (or 72\%)}$$

This means that as the number singers in a choir increases the probability of a significant result due to chance also increases. Here the result from applying Equation 6.4

demonstrates a 72% possibility of there being a statistically significant result due to chance, so Singers A and Q cannot necessarily be considered as significant, despite their *p*-values for *Test Piece* being under 0.05. To counteract the possibility of results being due to chance, the *Bonferroni* correction may be applied to the results (Goldman, 2008). This correction is applied to the conventional significance level of 0.05 to reduce the possibility of a significant result due to chance. It is implemented by dividing the chosen significance level (0.05) by the number of comparisons in Table 6.16 (25). The significance level is therefore reduced from 0.05 down to 0.002 (0.05/25) making the test far more discriminatory and the results less likely to be due to chance. Hence, the probability of one significant result due to chance is lowered as shown in Equation 6.5:

$$\text{Probability } = (1 - \left(1 - 0 \cdot 002\right)^{25}) \approx 0.49 \text{ (or 4.9\%)} \qquad 6.5$$

From the result of Equation 6.5 it may be seen that the likelihood of a chance occurrence of a significant result is reduced from 72% to 4.9%. Applying this revised significance level to the *p*-values of singers for the *Test Piece* (the second column of Table 6.16) it may be seen that no singer lies within the revised criterion of on, or under, 0.002 (0.2%). The same finding applies to the *p*-values for the chosen song (the fourth column of Table 6.16). However, the *Bonferroni* correction is considered to be conservative by setting the revised criterion too low which could lead to the rejection of a false H_0.

Inspection of the two sets of results for both songs highlights some similarities in certain singers' probabilities which, if they could be combined, might produce new set of results that might meet the *Bonferroni* criterion of significance. In his book, Fisher (1934) developed a *Combined Probability Test* which takes the probabilities from two or more sets of independently derived results and applies them using Equation 6.6. In the case here, the fact that two quite different songs were performed provides the required degree of independence (McConway, 2018), hence Fisher's method can be applied to the two sets of results for *Test Piece* and the chosen song.

Fisher's method provides a *chi-squared* (χ^2) result from which the new probability (p-value$_{\text{Fisher}}$) may be derived using the *Excel* worksheet function CHISQ.DIST.RT in Equation 6.6:

$$p\text{-value}_{\text{Fisher}} = \mathrm{CHISQ.DIST.RT}\{(-2\times\mathrm{LN}(p_{test\ piece} \times p_{chosen\ song}), 2\times DI)\} \qquad 6.6$$

where DI is degrees of independence, i.e. the number of results that are combined which here is 2 for the two separate songs.

Table 6.17 shows the results of applying Fisher's method to the singers' p-values of each song to generate a new set of combined probabilities. Singer Q now has a p-value$_{\text{Fisher}}$ of 0.002 which meets the *Bonferroni* criterion for significance. Whilst Singers A, E, I and N are not significant, they may still be of interest, given the conservative results returned by the *Bonferroni* correction. Regarding their effect on pitch drift; singers E and I are associated with a downward drift, whereas singers A, N and Q are associated with an upward drift.

Table 6.17 Results of applying Fisher's combined test to the individual probabilities of the two songs

	Test Piece		chosen song		Combined	
Choir D	***p*-value T**	**G/P rating**	***p*-value C**	**G/P rating**	***p*-value F**	**Attendance**
Singer A	0.028	2.400	0.068	2.000	0.014	60%
Singer B	0.795	-0.250	0.606	-0.500	0.833	75%
Singer C	0.194	-1.250	0.606	-0.500	0.370	75%
Singer D	0.391	0.950	0.653	-0.500	0.604	55%
Singer E	0.178	-1.500	0.074	-2.000	0.070	50%
Singer F	0.436	0.750	0.606	0.500	0.616	75%
Singer G	0.257	0.550	0.305	0.500	0.278	95%
Singer H	0.391	0.950	0.178	1.500	0.254	55%
Singer I	0.142	-1.600	0.068	-2.000	0.054	60%
Singer J	0.257	-0.550	0.305	-0.500	0.278	5%
Singer K	0.660	-0.350	0.531	-0.500	0.718	85%
Singer L	0.353	-0.450	0.305	-0.500	0.348	95%
Singer N	0.089	1.350	0.060	1.500	0.033	15%
Singer O	0.369	-0.800	1.000	0.000	0.737	80%
Singer P	0.413	0.650	0.531	0.500	0.552	85%
Singer Q	0.028	2.400	0.006	3.000	0.002	60%
Singer R	0.279	1.150	0.639	0.500	0.485	35%
Singer S	0.660	0.350	0.531	0.500	0.718	15%
Singer T	0.582	-0.600	0.361	-1.000	0.538	60%
Singer U	0.964	0.050	0.653	-0.500	0.921	45%
Singer V	0.391	0.950	0.178	1.500	0.254	55%
Singer W	0.142	1.600	0.361	1.000	0.204	40%
Singer X	0.069	1.750	0.606	0.500	0.175	75%
Singer Y	0.795	-0.250	0.121	-1.500	0.322	75%
Singer Z	0.582	0.600	0.361	1.000	0.538	40%

Whilst this is not a conclusive result it does reject the null hypothesis, that attendance patterns of individual singers within a choir do not have an effect on the irregular occurrence of pitch drift, in the case of Singer Q.

6.6.7 An alternative view on the effects of attendance

An alternative analytical method that demonstrates how the attendance patterns of individual singers may affect pitch drift may be achieved by constructing a scatterplot for each choir from the *p*-values for each singer for *Test Piece* against those of the chosen song. Figure 6.24 shows examples of the scatterplots for two choirs. It may be observed that each chart has clusters of singers appearing in the bottom left-hand corner (i.e. these singers have low *p*-values for both songs). Scatterplots for all the choirs can be found in Appendix 16.

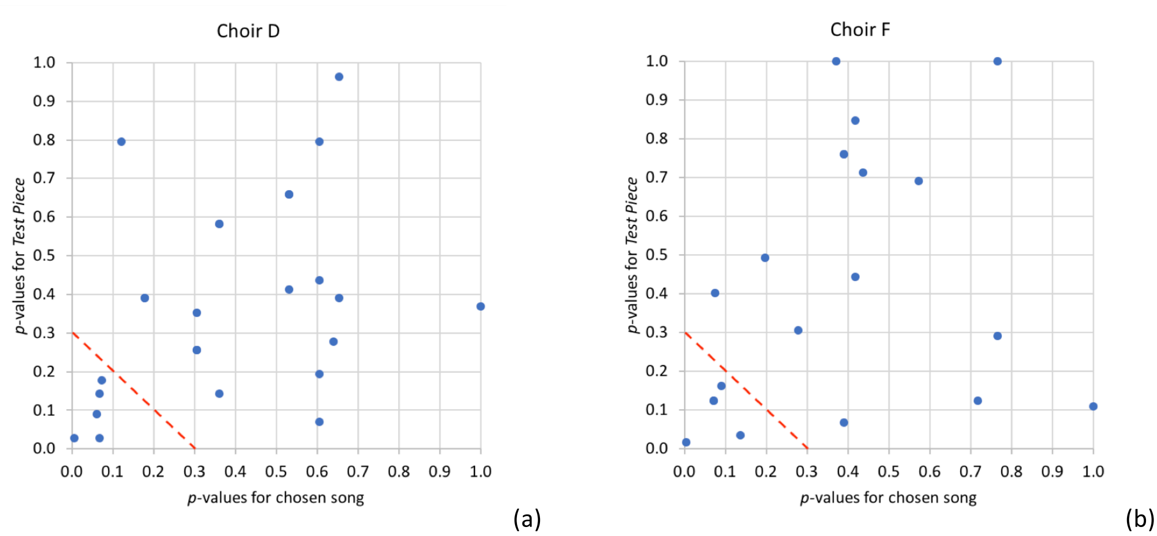


Figure 6.24 Scatter charts of *p*-values of both songs for the two choirs which demonstrated clusters of singers with significant *p*-values who may affect the pitch when they attend rehearsals (total = 20 for both charts)

The *p*-values of the clusters of singers in the bottom left-hand corner of the charts lead to the conjecture that they may have possible effects on pitch drift. In the case of the choirs shown in Figure 6.24, Singer Q in Choir D and Singer J in Choir F are significant (see Appendix 16). Unlike Table 6.17, this method does not allow any inference to be drawn directly as to whether the attendance of these singers is associated with pitch drift, but the *p*-values can always be cross-referenced with Table 6.17. The random positions of points over the remainder of each scatterplot, to the right of the red diagonal dashed-lines, demonstrates that the presence or absence of those singers is unlikely to affect the pitch-drift rating.

6.6.8 Summary

This section analysed the attendance pattern of singers against the degree of pitch drift experienced by their choirs. The statistical methods used were tried and tested and the results were verified using binary regression analysis with the *R* software environment for statistical computing[9] (this alternative statistical method is not available with *Excel 2016*).

Of the eleven choirs taking part in this research two choirs revealed that the attendance patterns of certain singers, with significant *p*-values, may have an effect on the pitch drift experienced by their choirs. This result supports the comments of one of the choral conductors (CC2) interviewed in sub-Section 4.4.1 who suggested that the presence at rehearsals of certain 'key-singers' could make a difference to pitch drift. This result will be discussed further in Chapter 7.

6.7 Environmental effects

6.7.1 Introduction

Suggestions that the environment in which a choir sings may affect pitch drift have been discussed in Sections 3.2, 3.3, 4.3 and 4.4. Within this research the tests on the environment consisted of two distinct procedures, logging the environmental factors within the venue during each recording and measuring the acoustic parameters of the rehearsal room.

[9] www.r-project.org (accessed 9 December 2018)

6.7.2 Environmental factors at rehearsals

This analysis investigates whether a relationship exists between the pitch drift at a rehearsal and any of three environmental factors – temperature, humidity and atmospheric pressure – that prevailed during that rehearsal. Light levels and background noise were also measured initially but when it became apparent during the experiments that these factors were not varying markedly between rehearsals, measurements of these factors were stopped, and they were ruled out as contributing to variations in pitch drift.

In this analysis, the pitch drift values were taken from the quantitative results (sub-Section 6.5.4) as they were in the same analogue form as the data for the environmental factors. Using the binary ratings for pitch drift (sub-Section 6.5.7) here would have meant converting the environmental factors to a binary form which was not seen as practical. Given there was on average a 91% agreement between the quantitative pitch-drift ratings and those of at least one of the adjudicators (Table 6.12) it was felt that the quantitative results were sufficiently accurate to be used independently to test for the existence of any significant relationships with the environmental factors.

The scatterplots shown in Figure 6.25 were created using the *Excel* regression analysis data tool introduced in sub-Section 6.5.8. They demonstrate the distribution of the pitch drift of a specific song against an environmental factor measured at the time of each recording in the rehearsals.

In Figure 6.25(a), pitch drift for the chosen song from Choir F's 20 rehearsals has been plotted against humidity (%). An R^2 value of 0.633 indicates a moderate likelihood that the occurrence of pitch drift may indeed be due to the effect of the humidity. In Figure 6.25(b), the pitch drift for *Test Piece* from Choir J's 12 rehearsals is plotted against the temperature readings (°C). An R^2 value of 0.548 indicates a possible effect on pitch drift due, in this case, to temperature. In addition to these charts, the *Excel* data analysis regression tool returns tabulated data for Choir F’s 20 rehearsals with respect to humidity, shown in Figure 6.26. The results for R^2 is highlighted in orange and probability is highlighted in dark red.

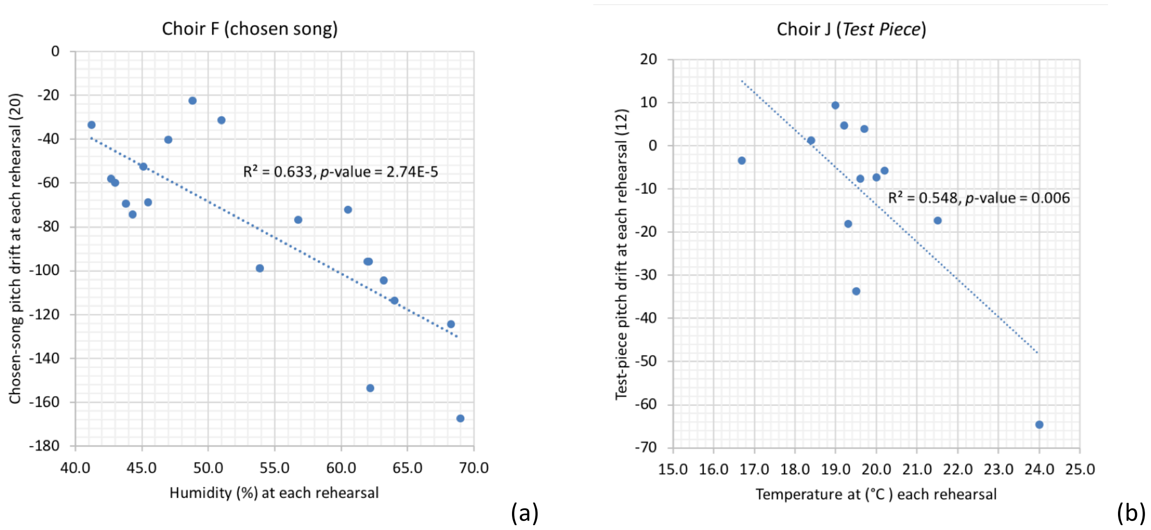


Figure 6.25 Scatterplots of two different choirs demonstrating pitch drift against: (a) humidity during a performance of chosen song (total = 20); (b) temperature during a performance of *Test Piece* (total = 12)

SUMMARY OUTPUT (Choir F chosen song)

Regression Statistics	
Multiple R	0.795615076
R Square	0.63300335
Adjusted R Sq	0.612614647
Standard Erroi	24.30138759
Observations	20

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	18334.90048	18334.90048	31.04676917	2.7395E-05
Residual	18	10630.0339	590.5574386		
Total	19	28964.93438			

	Coefficients	*Standard Error*	*t Stat*	*p-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	95.43853535	32.06416519	2.976485893	0.008088303	28.074224	162.8028467	28.074224	162.8028467
Humidity (%)	-3.277662609	0.588242015	-5.571962775	2.7395E-05	-4.513513223	-2.041811995	-4.513513223	-2.041811995

Figure 6.26 *Excel* regression analysis for pitch drift of Choir F’s chosen song against percentage humidity

Regression analyses for the three environmental factors were completed for all the choirs with the results presented in Table 6.18. Only the probabilities are shown as they are of interest to this research. The same colour-coding scheme as described in sub-Section 6.6.5 has been employed to highlight in dark red any *p*-value that suggests rejection of H_0, (i.e. *p*-values under 0.05). The combined probabilities for both songs were obtained using *Fisher’s* method (sub-Section 6.6.6). The inference is that changes in environmental factors during the rehearsals of the choirs in this research do not appear to have a significant effect on pitch drift. There is a slight possibility that these pitch drift results may have been confounded by the humidity results in the case of Choir F, and similarly the temperature results for Choir J. However, these two results are isolated and just as likely be due to chance, or indeed to the attendance interacting with the environmental factors. Moreover, applying the *Bonferroni* correction (sub-Section 6.6.5) reduces the significance level from 0.05 to 0.005 (to 3 decimal places). This rules out any significance in the temperature for Choir J although the significance of humidity for Choir F still stands. These results are discussed further in Chapter 7.

Table 6.18 Probabilities for each of the songs and the combined probabilities for the environmental factors: temperature, humidity and barometric pressure (corrected significance level = 0.005)

p-values	*Test Piece*			chosen song			Combined (Fisher)		
Choir	Temp (°C)	Hum (%)	Press (hPa)	Temp (°C)	Hum (%)	Press (hPa)	Temp (°C)	Hum (%)	Press (hPa)
A	0.866	0.372	0.523	0.575	0.454	0.451	0.845	0.469	0.576
B	0.979	0.774	0.188	0.429	0.353	0.181	0.784	0.628	0.149
C	0.095	0.031	0.362	0.278	0.508	0.673	0.123	0.081	0.588
D	0.366	0.319	0.404	0.519	0.351	0.037	0.505	0.357	0.077
E	0.384	0.847	0.068	0.095	0.609	0.985	0.157	0.857	0.248
F	0.491	0.011	0.673	0.320	0.000	0.570	0.448	0.000	0.751
G	0.914	0.319	0.199	0.917	0.072	0.986	0.986	0.110	0.516
H	0.146	0.803	0.987	0.879	0.463	0.622	0.391	0.740	0.914
I	0.493	0.814	0.486	0.152	0.042	0.268	0.268	0.148	0.395
J	0.006	0.607	0.419	0.372	0.448	0.998	0.016	0.626	0.783
K	0.153	0.398	0.810	0.810	0.394	0.477	0.382	0.447	0.754

6.7.3 Acoustic properties of the rehearsal venues

The three acoustic measurements employed in this research were described in detail in Section 2.3.7 and follow those of Howard and Moretti (2009) who used the standard reverberation time (T_{30}), the clarity index (C_{80}) and the early decay time (EDT) to describe acoustic properties in their study of the architecture of some of the most admired churches in Venice (Italy).

The acoustic properties of the venues in which the choirs rehearsed at the time of the experiments have been derived by processing recordings of impulse sounds generated at each venue using the audio editor *Audacity* together with the room acoustics plug-in *Aurora* detailed in sub-Section 5.3.5. Table 6.19 shows the values calculated by *Aurora* for each of the venues for the mid-band frequencies of 500 and 1000 Hz.

Table 6.19 Acoustic properties of the rehearsal venues

Choirs	Venue	Volume (m^3)	T_{30} (s)	C_{80} (dB)	EDT (s)
Choir A	Room	175	0.35	15.21	0.30
Choir B	Room	320	0.52	8.07	0.54
Choir C	Large church	3300	2.02	–0.12	1.69
Choir D	Large hall	2000	1.70	0.97	1.83
Choir E	Room	200	0.59	9.39	0.52
Choir F	Room	150	0.74	5.58	0.72
Choir G	Small hall	510	0.87	3.51	0.85
Choir H	Large church	1675	1.61	–1.62	1.60
Choir I	Small hall	650	1.03	4.78	1.05
Choir J	Large church	1700	1.43	–0.61	1.58
Choir K	Small hall	780	1.21	2.95	1.08

Four choirs use rooms which have low reverberation times of between 0.35 and 0.74 seconds. The remainder use either small or large halls or churches with reverberation times varying between 0.87 and 1.7 seconds. Given that the choirs rehearse in venues with such differing acoustic properties, it is interesting to see if there any correlation between these properties and the average pitch drift of the choirs. Each choir's average pitch drift for both songs taken from the quantitative analyses are set against each of the three acoustic parameters in turn. Note that this is not in any way comparing the performances of choirs but, because each choir always used the same venue, this is the only way of discovering if the acoustic parameters of the venues have any bearing at all on pitch drift. The charts shown in Figure 6.27 show the results from the *Excel* regression analysis plotted for each choir.

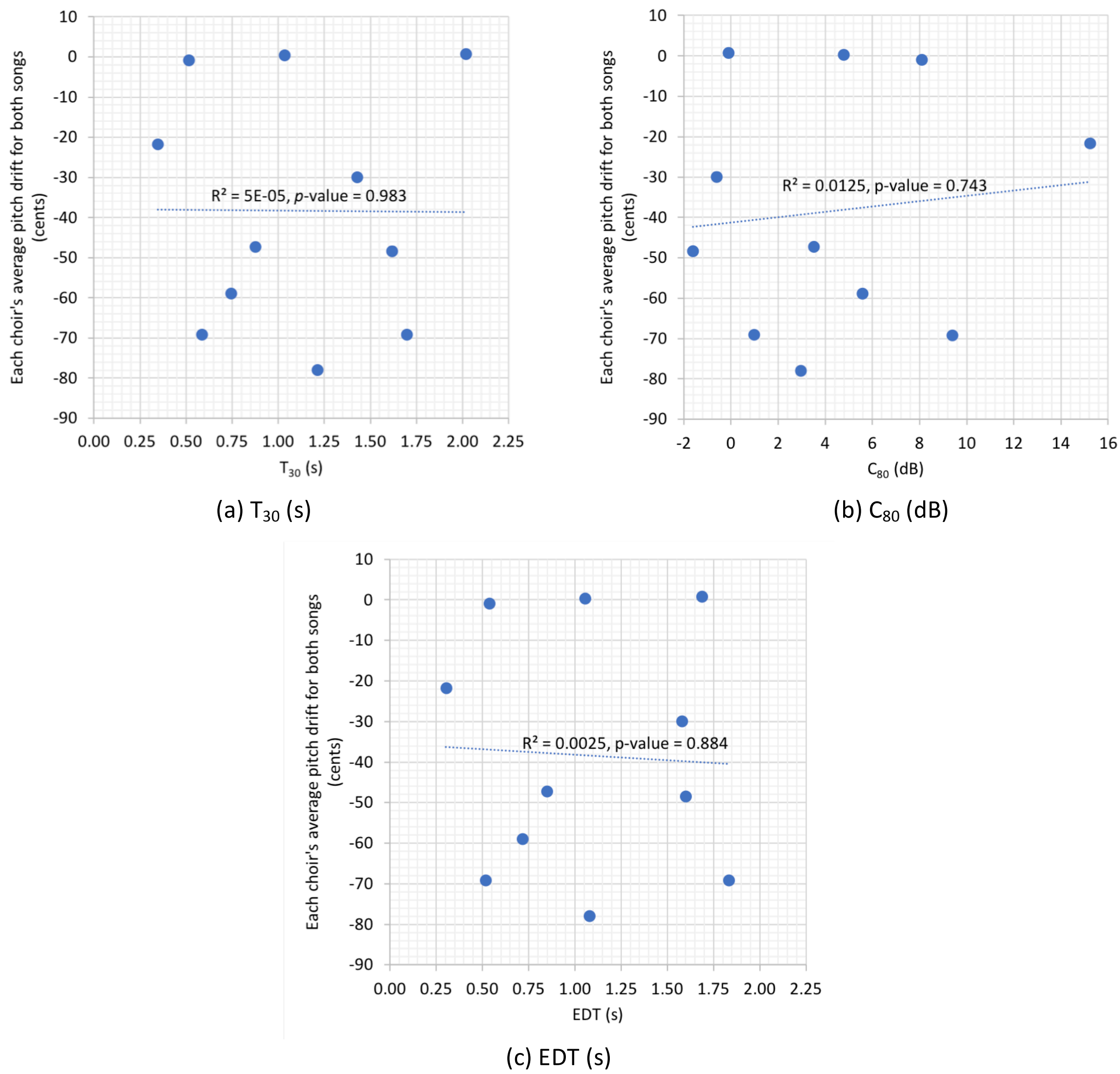


Figure 6.27 Plots of (a) T_{30}, (b) C_{80}, and (c) EDT against average pitch drift of each choir for both songs (total = 11)

From the data collected at the rehearsal venues, there is no correlation between any of the three acoustic properties (T_{30}, C_{80} and EDT) and the average pitch drift for both songs sung by each choir (Table 6.19). The scatterplots of the three acoustic properties of Figure 6.27 display random distributions with very low R^2 values with the *p*-values demonstrating no significance. Thus, the null hypothesis, that the acoustic parameters of rehearsal rooms have no effect on pitch drift, is not rejected. Predictions indicate that any single property would make less than 12 cents difference to the average pitch drift over the measured range, indicated by the slope of the dotted trend line. It has already been established that a pitch drift of less than 14 cents will not be noticed by the majority of choral practitioners so choirs need not be overly concerned about the acoustic parameters of their rehearsal venue affecting pitch drift.

6.7.4 Summary

No significant correlation was found in choirs' pitch drift against either environmental factors (temperature, humidity or atmospheric pressure) or differences in the acoustic properties of the rehearsal venues. The environmental factors certainly differed at the rehearsals but possibly not sufficiently to cause significant changes in pitch. The availability of central heating in the majority of venues tends to give a certain stability to both temperature and humidity even if they are not ideal for singers. The only factor outside human control was atmospheric pressure and the differing pressures measured on rehearsal days showed no correlation with pitch drift at all.

Whilst the research required that choirs made all their recordings in the same venue in case the changed acoustic properties of another venue might affect pitch drift, this may not have been necessary according to the above results. This will be discussed more fully in Chapter 7. However, keeping the changes in any rehearsal to a minimum was thought essential if the research was to produce any meaningful outcomes.

The final experiment discovers the abilities of singers to discriminate between different pitches. These results are covered in the following section.

6.8 Pitch discrimination survey

6.8.1 Introduction

The final experiment looked at the ability of singers involved in this research to discriminate between different pitches. This was based on the work of Seashore (1938) who found that the average person was able to detect the difference between two pitches if they are separated by approximately 12 cents or more based around a fundamental frequency of 435 Hz.

The issues addressed in this research were:

- whether choral singers have a better than average discrimination;
- to determine whether choirs that audition singers recruit individuals with better discrimination;
- to test if there is any correlation between pitch discrimination and pitch drift.

6.8.2 Review of the survey

The pitch discrimination survey was described in sub-Section 5.3.1. All 307 singers taking part in the experiments were encouraged to take part in this survey. An introductory letter (Appendix 12) was given to each singer and regular prompts were sent to the choirs' musical directors asking them to remind their singers to take part in the survey. Ultimately, 154 singers (50.8%) took part which was slightly disappointing but due possibly to the need to access the survey from a computer, something that not all singers were able to do. There may also have been a reluctance to take part given that the need for anonymity meant that the results could not be made known to the respondents. Interestingly, there was a large disparity between the numbers of responses from individual choirs; one attained a 77% response whilst another only returned a 20% response. All musical directors were asked to encourage their singers to take part – perhaps some stressed the importance of the survey more than others. Of the 154 responses, seven respondents appeared not to provide considered answers – they were identified by giving the same response to all the tests and not declaring their voice part in their choir. Taking these two factors together it was decided to exclude them, thus giving a final total of 147 responses, i.e. 48.5% of all singers.

6.8.3 Pitch discrimination abilities of singers

The results for each choir were downloaded from the survey's website in a comma separated value (CSV) format and saved in a standard *Excel* workbook format. The responses for all 147 singers were analysed, and the results are shown in Figure 6.28. The mean of the correct responses is 64.5% with standard deviation of 11.1%.

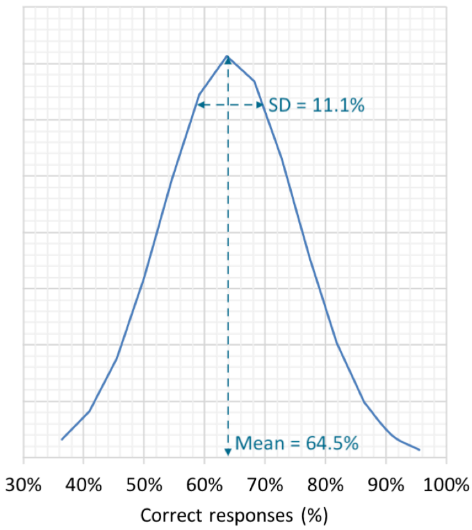


Figure 6.28 The mean and standard deviation for correct responses (total = 147)

Large differences in pitch between the tone pairs were usually recognised correctly apart from the occasional incorrect response that was assumed to be an unforced error in selecting the right answer. As the pitch difference narrowed to below ±20 cents fewer correct response were given, falling to around 10% at differences of ±4 cents and below, see Figure 6.29. However, an unexpected anomaly in pitch discrimination abilities arose when the results of discriminating between the two tones when second tone was lowered in pitch (i.e. flattened) were compared with the results when the second to was raised (i.e. sharpened) by the same amount. Figure 6.29 shows the results; the square points (blue line) indicating the correct responses of the singers when the second tone was lowered in pitch, the round points (red line) indicating the correct responses when the pitch of the second tone was raised. (The first tone was the same in all cases.)

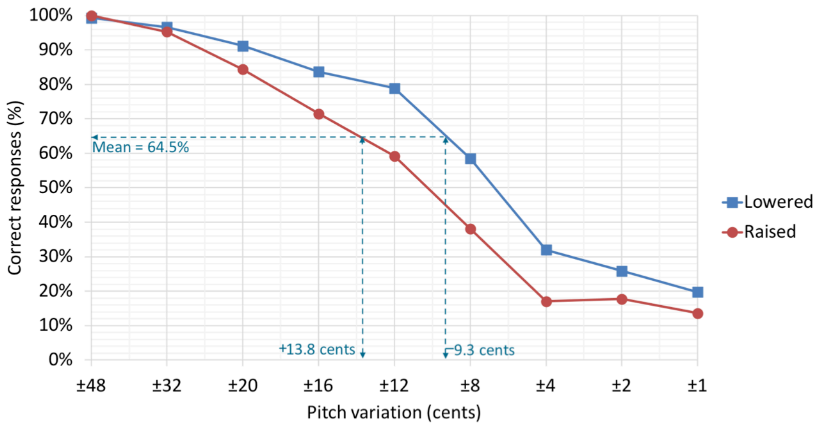


Figure 6.29 A comparison of the correct responses of singers to each tone pair when the second tone was lowered and when it was raised. Responses when the tones were equal are not shown as they were there only as a control (see sub-Section 5.3.1) (total = 147)

It may be observed that when the second pitch is lowered the singers' pitch discrimination is more discerning than when the second pitch is raised (i.e. the square-point blue line is always above the round-point red line after the first point (±48 cents)). There is a variance in discernment particularly when the difference between the tones is in the range of 2–20 cents with singers always better able to discriminate between two pitches when the second tone was lowered compared with the first tone. The horizontal dotted blue line in the figure is set at the mean level of the correct responses of 64.5%, taken from Figure 6.28. This line indicates respondents would, on average, be able to discriminate between two tones when the second tone is lowered by approximately 9 cents, while they would only be able to discriminate between two tones when the second tone is raised by approximately 14 cents. The average of these two discriminations is 11.6 cents which compares very favourably with the average of 12 cents found by Seashore (1938). However, he makes no mention of the differences due to the direction of the second tone as reported here.

6.8.4 Auditioned vs. non-auditioned singers

The second outcome considered whether auditioned singers had any discernible differences in pitch discrimination abilities compared with singers who were not auditioned. It was assumed that auditioned singers were likely to be more able and experienced singers. Whilst not related directly to pitch drift, these results may be useful to choirs who may be considering whether they should audition or not. To ensure anonymity, the results of choirs with a policy of auditioning singers have been totalled and presented in the first row of Table 6.20. The second row presents the results for those choirs which do not audition singers.

Table 6.20 Average correct responses for singers in choirs which do and do not audition singers (total = 147)

Audition	Respondents	Average correct response (%)
Yes	64 (46%)	63.9
No	83 (56%)	65.1

There being no significant difference between these two scores, the results suggest that choirs which have auditions do not appear to select singers who have better than average pitch discrimination abilities.

6.8.5 Pitch discrimination and pitch drift

The main purpose in conducting the pitch discrimination survey was to ascertain whether or not there was any correlation between the pitch discrimination results on a per choir basis and their pitch drift in each of the two songs performed at rehearsals as shown earlier in Figure 6.20. The results of the correlation exercise using *Excel's* regression analysis tool are shown in Figure 6.30.

The combined probability scores for both songs of 0.781 demonstrates that there is no correlation between the pitch discrimination and pitch drift. Thus, the null hypothesis, that pitch drift is not affected by the pitch discrimination abilities of singers, is not rejected.

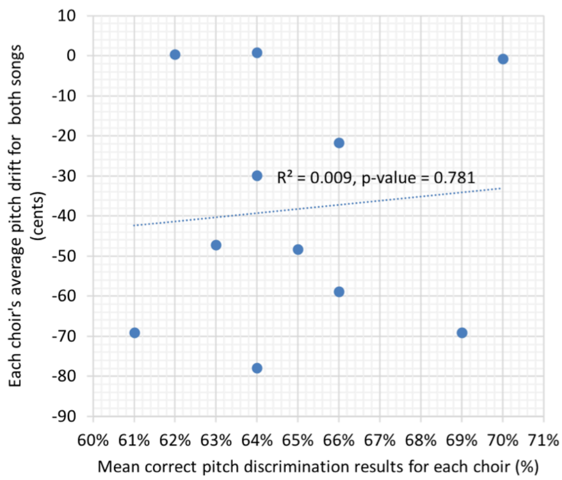


Figure 6.30 Pitch drift ratings for both songs against the mean correct pitch discrimination results for each choir (total = 11)

6.8.6 Summary

Overall, the singers responding to this survey demonstrated average pitch discrimination abilities as found by Seashore. Auditioning singers does not appear to result in the selection of singers with any better pitch discrimination abilities. Pitch discrimination abilities do not correlate with pitch drift of the choirs in which they sing. Finally, an anomaly in pitch discrimination abilities appears to exist when the second tone of a pair is lower in pitch compared with the case when the second tone is raised. These results will be discussed further in Chapter 7.

6.9 Chapter summary

This completes the presentation and discussion of the results from the three experiments to investigate why pitch drift varies between rehearsals. Listening to the *comparison-files*, created from the recordings of each choir (sub-Section 6.5.3) on the audio CD which accompanies this thesis, demonstrates that the degree of pitch drift varies to a greater or lesser extent from rehearsal to rehearsal. The three experiments, considering attendance, environment and pitch discrimination, were designed to try to determine possible causes of the variations in pitch drift.

An introduction to this chapter was followed by an overview of the recruitment campaign (Section 6.2). The reasons for recruiting particular types of choirs, based on the survey of choral practitioners, were stated. This was followed by a brief introduction to the eleven choirs who kindly agreed to take part in this research.

Section 6.3 looked at methods of measuring musical pitch – a vital requirement for this research. A brief history of pitch measurement was followed by consideration of the current computer applications that were available for pitch analysis and change, including systems for correcting pitch in real-time. It was stressed that most pitch analysis was usually carried out with solo voices or instruments and that applications working with complex chordal music were not so readily available.

Two applications which were capable of quantifying pitches within four-part choral music were considered in Section 6.4. Tests were undertaken using *Audition* from Adobe Inc. and *Melodyne Studio* from Celemony GmbH. Both applications are capable of measuring pitch in terms of note value and frequency. However, extensive testing showed *Melodyne* to be more suitable for this research as it offered automatic decomposition of complex sounds into notes and a clear display in which to measure the note values without any loss of accuracy when compared with *Audition*.

The rating of pitch drift was discussed in Section 6.5. A problem with a lack of feedback on pitch drift at rehearsals from the musical directors of certain choirs meant revising the planned method of rating pitch drift. To overcome this set-back two experienced musical directors of amateur choirs were appointed to rate pitch drift from all the recordings. Their qualitative ratings were reconciled with the results from the quantitative analyses to give a fair rating of pitch drift for each song in each rehearsal. The reason for using a binary scheme for rating pitch drift was also discussed.

The results from the first of the three experiments were presented in Section 6.6. This related the pitch drift rating to the attendance of singers at each rehearsal. Whilst it has not been possible to prove that the attendance of certain singers affects their choir's pitch drift with all the choirs, there does appear to be a slight to moderate correlation with two choirs. These results may have been more significant if all choirs had returned data for all 20 rehearsals.

Section 6.7 looked at the effects of environmental change on pitch drift. No significant correlation between pitch drift and changes in temperature, humidity or atmospheric pressure on pitch drift could be demonstrated. Whilst the acoustic properties of the choirs' rehearsal venues differed considerably, no significant differences were found to the average pitch drifts between the choirs.

Finally, the pitch discrimination survey, presented in Section 6.8, demonstrated that, whilst auditioning singers may be important to choirs needing singers with specific choral skills, the pitch discrimination of their singers is likely to be no better or worse than those in choirs not requiring auditions. Also, the pitch discrimination ability of singers appears to be similar to those of the general population as reported by Seashore. There was no correlation found between the pitch discrimination abilities of singers and the pitch drift experienced by their choirs. The results also highlighted an unexpected mis-match in the ability of the singers to discriminate between two tones when the second tone was lowered in pitch compared with the first tone to when it was raised in pitch. At the time of writing there does not appear to be any literature which has reported this finding.

The final chapter in this thesis discusses the findings from these results and will look at possible future avenues of investigation.

Chapter 7

Outcomes and suggestions

‘But there’s people set up their own ears for a standard and expect the whole choir to follow ‘em.’ (*Silas Marner*, George Elliot, 1861)

7.1 Pitch drift in *a cappella* choral singing

7.1.1 Introduction

This research has investigated the variability of pitch drift in *a cappella* singing by amateur choirs. Anecdotal support for this phenomenon’s existence are not lacking, nor are speculative explanations; but it has received little, if any, empirical investigation.

Based on the outcomes of the experiments with eleven amateur choirs, this thesis makes the following distinct contributions to knowledge.

- In repeated performances by amateur choirs of the same pieces, over an extended period, the degree of pitch drift is inconsistent both within and between choirs. Furthermore, the pitch is much more likely to drift downwards, than upwards even in pieces judged to be overall ‘pitch neutral’ (Chapter 3).

- There is some evidence that the patterns of attendance by singers can affect pitch drift, and that certain ‘key-singers’ are influential. However the size of the choir does not appear to have an effect on pitch drift.

- Variations of temperature, humidity and atmospheric pressure, within the range experienced within the United Kingdom, have no significant effect on the variability of pitch drift.

- Pitch discrimination of singers in this research was, on average, no better than that of the general population.

These contributions to knowledge were founded on three avenues of research. Firstly a literature review confirmed that pitch drift does occur in *a cappella* performances and suggested possible causes included the music, singers' techniques, room acoustics and environmental factors. Secondly, a survey of choral practitioners together with interviews and correspondence with some of the United Kingdom's leading choral musicians, reinforced the findings of the literature review and introduced other possible causes of pitch drift. Finally, the results of the experiments with amateur choirs have generated new findings as well as reinforced existing knowledge and, to a degree, has dismissed some of the beliefs into the causes of pitch drift.

7.1.2 Internal influences on pitch drift

Prior to this research the foremost reason offered as to the cause of pitch drift in *a cappella* performances is the manner of the composition of the music. The music may be considered as an internal influence on pitch drift. The elements that be can analysed within the music itself include; melodic contours, harmonies, intervals, key and key changes. Throughout this thesis it has been acknowledged that certain *a cappella* pieces are likely to drift in pitch during their performance due to the intonation of pitches and intervals, which can be at variance with those found on today's equally-tempered instruments (Chapter 2). Ongoing research by Howard (2007, 2013, 2015, unpublished) was introduced to demonstrate the way certain intervals are pitched cause the overall pitch to drift from that set by the composer (Chapter 3). He demonstrated both theoretically and practically that the way the music itself had been composed could cause the pitch to drift either sharp or flat or, in some pieces remain neutral, by the end of the performance. Howard confirmed this empirically, both with his own specially written compositions and with well-known *a cappella* works from the Western choral repertoire. Indeed, the music originally selected for use with this research (*Heraclitus* by Stanford and the specially composed *Test Piece* by Pim) were both tested by Howard and found to be neutral.

Whilst there is no doubt that the composition of the music is a contributory factor to pitch drift, factors purely internal to the music cannot alone be held responsible for the irregular changes in pitch drift in different rehearsals. Anyone who doubts that such changes occur need only listen to the recordings of the eleven amateur choirs regularly performing the same music in up to twenty rehearsals on the audio CD that accompanies this thesis. These recordings confirmed that for the same piece of music the pitch drifted to a greater or lesser extent, despite the piece being rehearsed regularly (Appendices 14 and 15). Taking all the amateur choirs who took part in this research into consideration the pitch drifted down in nearly 80% of their rehearsals. This is reflected in the findings from the survey of choral practitioners where just over 90% of the respondents declared that when the pitch drifts it goes down rather than up (Section 4.3.4, Q15). This result suggests that there must be external influences affecting the ability of the choirs to maintain pitch as at least 68% of the music sung by the choirs in this research was rated as being pitch-drift neutral by Howard.

7.1.3 External influences on pitch drift

This research has confirmed two viewpoints regarding pitch drift: firstly, that in a majority of amateur choirs their pitch goes down rather than up; secondly, that pitch drift varies from rehearsal to rehearsal. Both of these views were hypothesised in Chapter 4 and have been confirmed subsequently by experimentation and analysis to be largely true for the cohort of choirs taking part in this research. The reason why the pitch usually goes down is outside the scope of this research, but if it happens to a similar degree at every performance then the drift is most likely to be due to the music – an internal influence as suggested in the previous section. However, if pitch drift occurs irregularly, as clearly demonstrated from the rehearsal recordings of the choirs taking part in the experiments, then the influence is likely to be external, i.e. factors that cannot be identified in the music itself. The results from the quantitative data suggests that amateur choirs exhibit such variability in singing intervals as to suggest little or no systematic use of any particular temperament. Possibly in professional or experienced amateur ensembles, with only one or two voices to a part, the intervals can be suitably modified in a methodical fashion, but such choirs would be the ones least affected by pitch drift, as was observed in the pitch drift data of the three better performing choirs in this research. However, this still does not fully answer the question of why degrees of pitch drift differ at and between rehearsals. Two external influences on pitch drift were considered: firstly, the effects due to changes in the attendance patterns of the singers; secondly, the variations of the environmental factors in the rehearsal room. In addition, the acoustic properties of the rehearsal room and the pitch discrimination abilities of the singers were also considered.

7.1.4 The effect of attendance on pitch drift

Two choirs taking part demonstrated a slight to moderate correlation between the variation in pitch drift and the attendance pattern of singers at regular rehearsals (Section 6.6.7). Unfortunately, no correlation could be found in the case of the other choirs (Appendix 16). The analysis procedures assured the results were as fair as possible by using well-established statistical methods to reduce the likelihood of significant outcomes being due purely to chance (Section 6.6). Whilst the survey of choral practitioners highlighted individual vocal parts as being a possible cause of pitch drift (Section 4.3.4, Q18), the attendance patterns of individual singers was not mentioned. Of course, a vocal part that is susceptible to pitch drift could cause other parts to drift. The influence of individual singers was emphasised in an interview with one of the choral conductors (CC2 in Section 4.4.1), who acknowledged the role of key-singers in having an effect on pitch drift. Whilst the effect of key-singers can only be observed in two choirs, they both returned a full set of results from 20 rehearsals, along with only three other choirs (Appendix 14). In hindsight even twenty weeks was probably insufficient to achieve significant results. This suggests that future experiments of this kind should be run over a longer period of say of twelve months.

7.1.5 Environmental factors

Despite suggestions to the contrary expressed in the literature review (Section 3.2), the survey (Section 4.3.4, Q18) and the interviews (CC3 in Section 4.4.1), no significant correlation could be found to exist between pitch drift and variations in the environmental factors as experienced by the cohort of choirs within their rehearsal venues. From the analyses of temperature, humidity and atmospheric pressure (Section 6.7.1), two choirs demonstrated a slight correlation – one related to humidity and the other to temperature. However, one of these two choirs also showed a significance due to attendance patterns which may be confounding the environmental results (or vice versa). This does raise the important point that the two independent variables; attendance and environmental factors, may be interacting in some way, but given the lack of correlation of environmental factors against pitch drift in the majority of cases, any interaction may be discounted. This could be proven by ensuring one or other of these variables remained constant. In the case of the environmental factors, this would be difficult to achieve, particularly with atmospheric pressure, and whether it would be possible to achieve 100% attendance is also open to debate! However, given the results from this research it does appear that environmental factors within the rehearsal venue do not appear to play a significant part in the irregular variations of pitch drift. The possibility that the effects on singers of outside environmental factors (i.e. the weather conditions) may affect pitch drift were not tested but cannot be ruled out.

7.1.6 Acoustic parameters

Comparisons between the overall pitch drift experienced by choirs and the acoustic parameters of the wide range of rehearsal venues, showed no correlation despite the fact that very different acoustic parameters were measured (Section 6.7.2). The survey revealed that 58% of the respondents' choirs rehearsed in either a room (34%) or small hall (24%). Churches and cathedrals made up another 33% with just 9% using large halls (Section 4.3.3, Q9). However, church choirs usually rehearse in practice rooms rather than in the main body of their building so there may have been more choirs choosing smaller spaces in which to rehearse than were reported in the survey. The literature review stressed that the pitch will be better maintained when the singers are able to hear one another (Section 3.3). The acoustic parameters in the rehearsal room may support this effect but given that choirs usually perform to the public in venues with very different acoustics, choirs must try to rehearse in the new environment prior to any public performance to allow acclimatisation to the new acoustic parameters.

7.1.7 Pitch discrimination tests

The final experiment was to test the pitch discrimination abilities of the singers taking part in this research. The results demonstrated that their pitch discrimination abilities were nominally the same as those of the population as a whole – based on A4, 440 Hz, (Section 3.4.1). In a recent paper on factors affecting pitch discrimination, Smith et al (2017) found an average threshold for 918 subjects being able to tell two pitches apart was 14.5 cents – based on a frequency of 1000 Hz; this reduced to 6.19 cents for the top 5% of participants. However, Smith's results supported both the findings here and those of Bradshaw and McHenry (2005) and Pfordresher and Brown (2007) – that singing abilities were largely unrelated to pitch discrimination. Moreover, no significant difference was found in choirs which audition their singers (although it is appreciated that choirs who audition may be seeking other qualities in their singers). One unexpected outcome from the pitch discrimination tests was that the singers were able to discriminate more readily between two pitches when the second pitch was lower than the first rather than when it was raised (Section 6.8.2) meaning a greater acuity to flattened notes over sharpened ones. Any further consideration of this outcome is outside the scope of this research but it deserves further investigation.

7.1.8 Auditions

Choirs that audition singers may attain higher standards in some aspects of choral singing more readily than those with an 'open-door' policy – such as the blend of the voices – but none of the analyses undertaken in this research show any significant differences in the pitch drift ratings of those choirs who audition singers against those who do not. Of the three choirs with above average ratings two of them audition singers and one does not. Thus there is no conclusive evidence that auditioned singers make any significant difference to pitch drift.

7.2 Scope for future investigation

7.2.1 Direction of pitch drift

Choirs singing *a cappella* music drift down in pitch (i.e. go flat) rather than drift up (i.e. go sharp) was the overwhelming conclusion from the survey of choral practitioners. This was supported by the quantitative analysis of the choirs which found pitch drifting down in just under 80% of their recordings (Appendix 15). This raised two issues both of which are considered worthy of future research. Foremost is why pitch flattens on most occasions even when the note analysis demonstrates the music to be neutral or even possibly to go sharp. There must be influences at work, other than those discussed in this thesis, that cause this downward change in pitch. Does the pitch go down because singers believe it will happen? Do the majority of amateur singers have poor singing techniques? Should musical directors encourage singers to sing sharp? The second issue is on similar lines but focuses on the question as to why certain choirs in this research – generally those whose pitch drifted less – drifted sharp as often as flat by small degrees (Appendix 15). Given these choirs experienced less pitch drift than average may indicate that they are trying to ensure the pitch is not flattened and thus end up sharp. Unfortunately, no ‘key-singers’ could be identified as affecting the pitch in these particular choirs so the reasons remain unresolved by this research.

7.2.2 The pitching of the first note

An observation made whilst analysing the recordings of the choirs concerns the inconsistency in the pitching of the first notes in the chord at the start of a piece. Musical directors always gave an initial pitch, either the key note or a spread chord, which was usually within ±10 cents of the required pitch. The variation in the sung pitch of the initial chord could differ from the given note by as much a semitone high or low both within a vocal part (i.e. between singers in that part) as well as between the vocal parts themselves. These initial inaccuracies in pitch were unexpected and have not been investigated further within this research as the experiments were not designed with this phenomenon in mind, (only chords near the start and end of each song were measured to determine the overall pitch drift). As an example, the spread of pitches in the soprano voice part alone of the initial chord of one recording of *Test Piece* showed a variation of 257 cents whilst the singers attain a stable pitch (Section 6.5.5).

Investigating initial pitches is problematic for, after the choir has sung the first chord once, anecdotal evidence suggests the choir’s pitch on a second attempt will be much closer to the required pitch and more unanimous within each vocal part. This leads to the impression that some singers in amateur choirs need to be ‘tuned-in’ to the correct pitch by singing the initial note rather than just hearing it. Vocal training and practice at matching the sung pitch to the given pitch using a visual chromatic tuner may assist choirs in achieving a greater accuracy and unison of pitch at the start of a piece (Section 4.4.1). Whether the overall pitch drift would benefit from achieving a greater accuracy at the start of the song is uncertain, but is unlikely to make it any worse.

7.2.3 Pitch drift related to song length

It was observed from a comparison of the average good pitch drift ratings that the chosen song drifted more than *Test Piece* (Appendix 15). There is also evidence that the adjudicators found *Test Piece* more difficult to analyse. They disagreed on 61 occasions when analysing *Test Piece* compared with 39 occasions for the chosen song (Appendix 14). This is an interesting outcome which suggests that pitch drift may be related to the length of the song, given that the chosen songs took on average three times longer to sing (an average of 135 s) than *Test Piece* (an average of 43 s). Future research is needed to ascertain whether this difference is due to the number of note intervals, modulations and possible key changes (which would support an internal view of pitch drift above) or to the tempo at which the piece is performed. However, this would run counter to the findings of Section 3.3.2 that suggests pitch drift is less likely to occur when a slower tempo in employed. Of course the reason may be totally unrelated to the above hypotheses but seems worthy of investigation.

Another area of interest that arises from this finding is the assumption that pitch only drifts so far from the original key no matter the length of the piece. This would need to use pieces in which several verses employing identical music and words are sung.

7.3 Finale

This research broke new ground in the area of *a cappella* choral singing by using a cohort of amateur choirs performing the same two songs over an extended period in their usual and familiar surroundings. Despite all the many challenges, this research methodology involving amateur choirs from around the UK has been proven to work successfully. It was a real pleasure for the author to meet and work with so many enthusiastic singers, musicians, colleagues and friends over the period of this research.

The initial impetus for this research was the realisation that pitch drift differed from rehearsal to rehearsal in the amateur choir in which I was singing. The fact I was not present the week before when the choir kept pitch very well may just have been the reason why the pitch drift was worse in the rehearsal I was attending.

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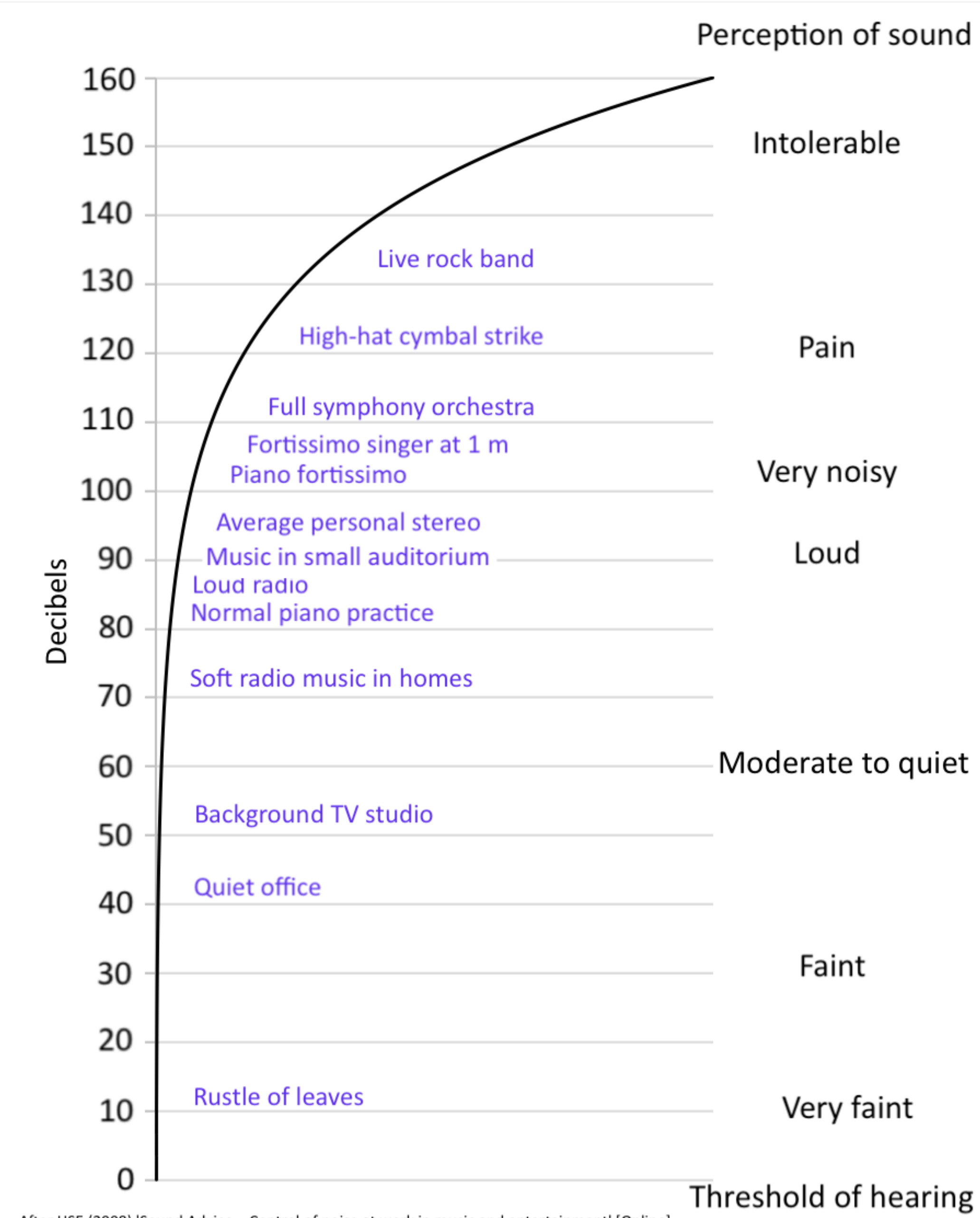
Appendices

Appendix 1 List of common sound pressure levels



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Appendix 2 The survey of choral practitioners

Pitch drift in 'a capella' choral singing

Dear Choral Practitioner

I am a PhD student in the Acoustics Research Group at The Open University researching into the subject of 'Pitch drift in a cappella choral singing'. Before designing and undertaking any experiments I want to find out as much as I can about possible causes and would appreciate your taking a few minutes to complete my survey.

My research is specifically about pitch variation in unaccompanied singing (either where whole pieces are unaccompanied or where the music includes substantial unaccompanied sections), so the survey may not be relevant if your choir does not normally sing such music. However, your responses are valuable so do please complete sections you feel may be helpful to me.

To avoid duplication this survey may only be completed once from any computer location. If you conduct more than one choir then please respond with details of the choir which you consider will be of most interest adding comments as necessary. If you prefer to complete paper surveys please email pitch.drift@open.ac.uk stating how many forms you will need. Return envelopes will be provided.

Note that you and your choir may remain anonymous if you wish and all information provided will be treated in the strictest confidence and made anonymous before use in any research paper, presentation or publication.

I am very grateful to you for taking time to complete my survey, it should only take you a few minutes to complete.

Richard Seaton.

Please use a separate sheet for additional comments where necessary.

Section 1, about your choir:

This section is asking for details about your choir.

1. Please give the name and website of your choir.
(You may leave all or part of this question blank if you prefer)

Choir's name:

Choir's location:

Website address:

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2. Which description most closely describes your choir?
(Please choose one option and use the box below to add details about your choir)

- ◯ Barbershop or Sweet Adelines
- ◯ Chamber choir
- ◯ Choral society
- ◯ Community choir (adult, children's or mixed)
- ◯ Vocal Group
- ◯ Other (please use the box below to describe)

Details about your choir (optional)

3. Please tick the boxes that cover the type of repertoire you mostly sing.
(Additional information may be added in the box below.)

- ☐ Medieval
- ☐ Renaissance
- ☐ Baroque
- ☐ Classical
- ☐ Romantic
- ☐ Early 20th century
- ☐ Modern
- ☐ All of the above

Additional information

4. At any given rehearsal approximately how many choir members are:
(Please complete all boxes that apply)

under 18?

18 to 29?

30 to 50?

over 50?

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5. How many FEMALE singers are there in each part in your choir? (Please complete all boxes that apply)

Soprano/Treble:

Alto:

Tenor:

Bass:

6. How many MALE singers are there in each part in your choir? (Please complete all boxes that apply)

Soprano/Treble:

Alto:

Tenor:

Bass:

7. How would you best describe the singers in your choir? (Please note that professional musicians who do not make their main living as singers should be included as amateurs in your response) (Please choose one option and add any comments in the box below)

- All professional
- Professional and experienced amateur
- Auditioned amateur
- Un-auditioned amateur

Comments: (optional)

8. Approximately what percentage of your singing is unaccompanied?

Percentage:

Section 2, about your rehearsal and venue:

This section is looking at where and how you rehearse.

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9. How would you describe the place in which you usually rehearse? (Please choose one option and if you wish add a description of the venue in the box below)

- ◯ Room (e.g. residential, office , classroom, etc.)
- ◯ Small hall (seating fewer than 200)
- ◯ Large hall (seating more than 200)
- ◯ Modern church building
- ◯ Traditional parish/country church building
- ◯ Cathedral or Minster-sized building
- ◯ Other (please use the box below to describe)

Description of the venue (optional)

10. On which day or days do you normally meet, what time do you start, and for how long do you usually rehearse?

Practice day (s):

Start time:

Duration of practice:

11. How would you assess the acoustics of your rehearsal venue? This ranges from no reverberation (dry) to being very reverberant (wet) (Please choose the most appropriate option)

No reverberation (dry)	Little reverberation	Some reverberation	Quite reverberant	Very reverberant (wet)
◯	◯	◯	◯	◯

12. Do you mostly perform in the place where you rehearse? (Please choose one option and add any comments in the box below)

- ◯ Yes
- ◯ No

Comments (optional)

Pitch drift in 'a capella' choral singing

13. In rehearsal do your singers mostly:
(Please choose all options that apply)

- [ ] sing grouped in parts (if appropriate)?
- [ ] sing standing?
- [ ] sing sitting?
- [ ] use tonic sol-fa?
- [ ] sing without scores?
- [ ] incorporate movement/choreography into their singing?

Section 3, about the maintaining pitch during unaccompanied singing:

If, in the past, your choir has suffered pitch drift, but, for whatever reason, this is not now a problem, please answer these questions for the past situation. Please use Question 18 to describe how and/or why pitch drift was resolved.

14. In rehearsal how often have you noticed that the choir as a whole tends to drift off key during unaccompanied singing?
(Please choose the option which is most appropriate)

- ○ Very rarely or not at all?
- ○ Occasionally?
- ○ Regularly?

15. If your answer in Question 14 is 'occasionally' or 'regularly' then does pitch drift move the key:
(Please choose one option and add any comments in the box below)

- ○ usually sharp?
- ○ usually flat?
- ○ as often sharp as flat?

Comments (optional)

16. If your answer in Question 14 is 'occasionally' or 'regularly' then does pitch drift occur:
(Please choose the option which is most appropriate)

- ○ early in the rehearsal?
- ○ towards the end of the rehearsal?
- ○ any time in the rehearsal?

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17. If your answer in Question 14 is 'occasionally' or 'regularly' then is the pitch drift something you are concerned about?
(Please choose one option and add any comments in the box below)

- ◯ Yes, because it happens too often.
- ◯ Yes, because when it happens the drift is severe (a semitone or more).
- ◯ Yes, because the drift both happens too often and is too severe.
- ◯ No, I am not concerned about pitch drift.

Comments (optional)

18. Having established that pitch drift does occur do you have any ideas as to why this happens, whether or not this occurs with, or is a problem with, your particular choir?

19. Please list any repertoire, or perhaps specific sections in particular pieces, that you consider prone to pitch drift:

20. In performance, do you notice whether pitch drift is:
(Please choose the option which is most appropriate)

- ◯ unlikely or never to occur?
- ◯ less obvious than in rehearsal?
- ◯ about the same as in rehearsal?
- ◯ worse than in rehearsal?
- ◯ unimportant, whether it occurs or not?

And finally, about you:

Thank you for completing the survey. All results will be treated in the strictest confidence and made anonymous before use in any paper, presentation or publication to do with this research.

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Pitch drift in 'a capella' choral singing

***21. Please choose the option which best describes your musical relationship with your choir.**

- ◯ Accompanist
- ◯ Assistant conductor
- ◯ Choral Director/Conductor/Leader
- ◯ Singer
- ◯ Other (please use the box below to describe)

Your role with your choir

22. If you would like to be kept informed of the progress of the research and possibly help with further investigations, please include your email contact details below (your email address will not be forwarded to anyone else and will only be used in connection with this research):

Name:

Email:

Many thanks for completing this questionnaire. Your contribution will be very helpful deciding the type and form of experiments necessary for my research. If you would like to contact me directly the project email address is pitch-drift@open.ac.uk.

Kind regards,

Richard Seaton.

Please now press 'Done' to finish and submit your responses to this questionnaire.

Appendix 3 Trifold flier which advertised this research project

The Open University

Pitch drift
in
a cappella
choral singing

a research project
by
Richard Seaton
PhD student at the Open University

Pitch Drift website:

http://acoustics.open.ac.uk/pitch-drift

Email address:

pitch-drift@open.ac.uk

Contact address:

Pitch Drift Research
Acoustics Research Group
MCT Faculty
The Open University
Walton Hall
Milton Keynes MK7 6AA
United Kingdom

Telephone:

+44 (0) 1908 653924

Picture detail from:
Graham Mills *This Land is Our Land (2007)*
Purchased by the OU Artwork Group in 2008

Speak to any choral practitioner about singing music unaccompanied, i.e. *a cappella*, and they'll come up with various suggestions as to why choirs drift in pitch from time to time.

My research attempts to find out if there are physical reasons why pitch drift occurs and suggest possible strategies to resolve the problem.

A survey has been designed to ask you about your choir, your rehearsals and your opinions as to possible reasons for the occurrence of pitch drift.

Please take a few minutes to complete the survey which you will find on the Pitch Drift website, details overleaf.

Alternatively, a survey form and reply envelope may be obtained by emailing, telephoning or writing to the project team.

All replies will be treated in strictest confidence and used anonymously.

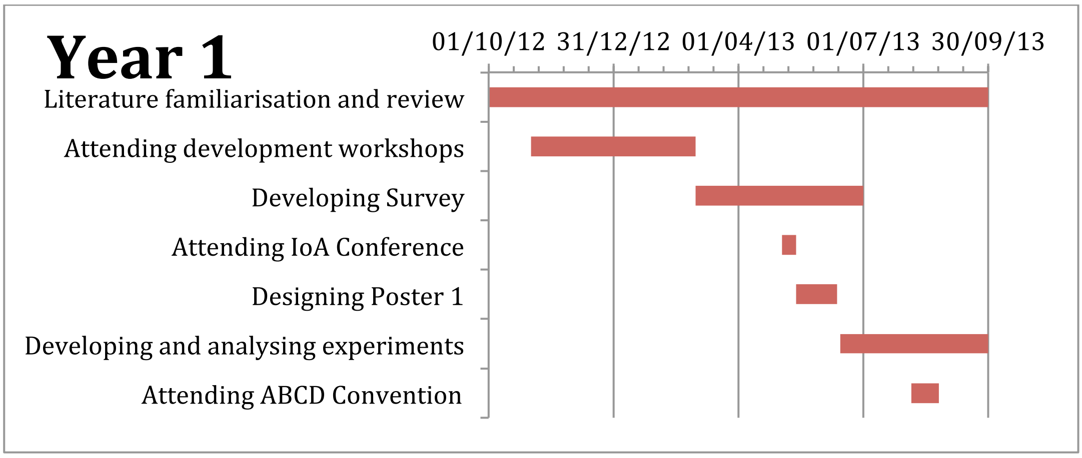
Thank you for your interest,

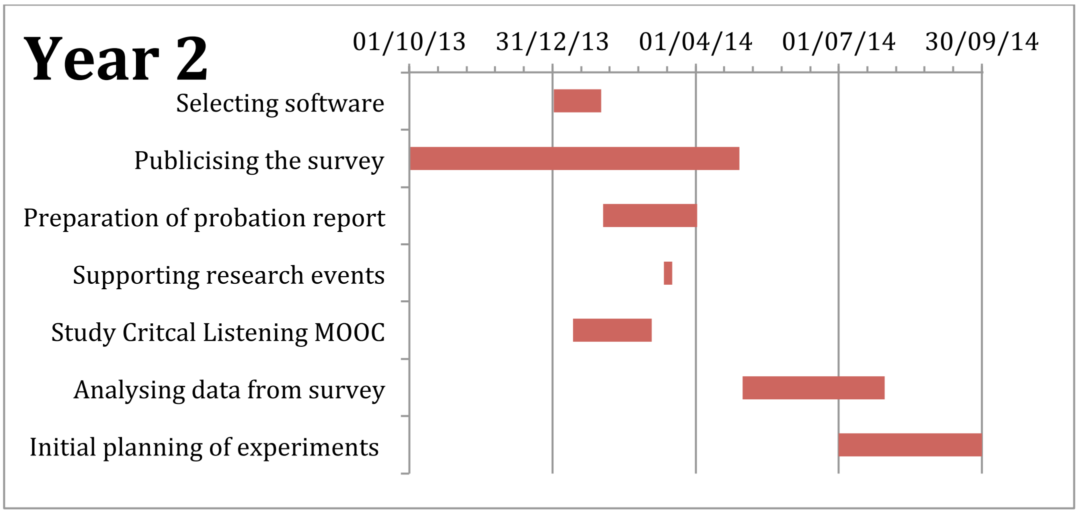
Richard Seaton

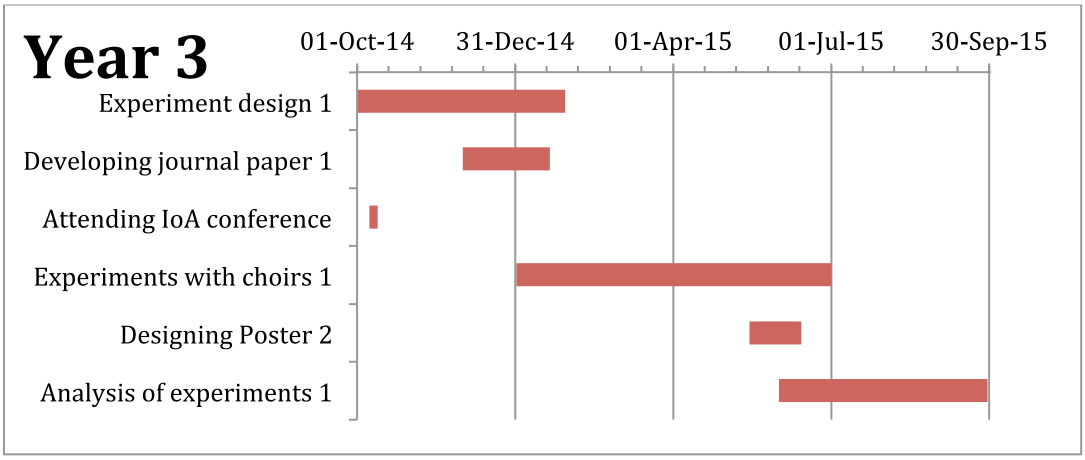
My poster shown inside was a winning entry in the OU's Poster Competition held in June 2013. It provides further details about the project.

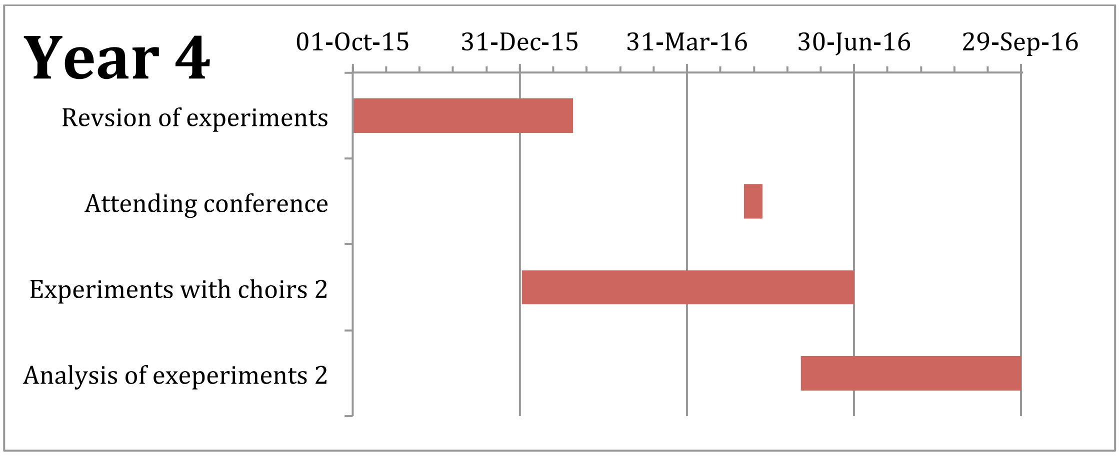

Pitch drift in *a cappella* choral singing
Supported by the OU Acoustics Research Group [http://acoustics.open.ac.uk]
Supervisors: Dr. Dennis Pim and Dr. David Sharp
PhD project by Richard Seaton
Faculty of Mathematics, Computing and Technology, Milton Keynes, MK7 6AA, UK
Telephone: +44(0)1908 655067 Email: richard.seaton@open.ac.uk
The Open University
Abstract
The research subject considers why choirs are not able always to maintain the pitch of the piece of music when they are performing *a cappella*. That is to say, when the performance requires no instrumental accompaniment or when the accompaniment is removed for musical effect and then, at some time later, reintroduced. In the case of the former, the drift from the intended pitch may not be so obvious to an audience other than to those with knowledge of, and the ability to recognize, the pitch. In the case of the latter, however, the reintroduction of instrumental accompaniment will make any drift in pitch very obvious. A literature review is ongoing and a survey of choral conductors, animateurs and directors is in hand. The responses to a pilot survey are summarized here.
Pitch
soprano
mezzo soprano
alto
tenor
baritone
bass
C4 A3 F3 C3 F2 E2 C6 A5 F5 C5 F4 E4
C1 C2 C3 C4 C5 C6 C7 C8
(middle C)
Pitch is a qualitative attribute of a musical sound which defines its position within the musical scale, known as the note. It is established by the frequency of the sound waves in Hertz (Hz), which act as a sensory stimulus. Pitch is heard to change when the frequency is changed and the amplitude held constant. In early polyphonic choral music, c. 1450, the relative pitch would be dictated by the differences of the human voice due to the physical attributes of the singers. Since 1939, 'concert pitch' has been defined as 440 Hertz for the note A4.
Diagram from OU Module *The Technology of Music* (TA212) Block 3:2
National survey of choral directors
The survey consists of three sections covering choir details, rehearsals and venues, and maintenance of pitch during *a cappella* rehearsals. The aim is to find out not just about the possible causes of pitch drift in the opinion of a wide range of choral practitioners but to investigate whether any particular choral genres are affected more than others. It may not be possible to experiment with every genre, and so gaining evidence through a survey will be valuable in reaching possible conclusions as to the reasons for pitch drifting. A pilot survey of five choirs has provided some useful data, although, as expected, the choral directors all gave different reasons for why they thought pitch drifts. Some of their responses are quoted in the picture below.
"acoustic conditions in the rehearsal room"
"when the music is being learned"
"poor vowels and in particular diphthongs"
"when one voice or more tries too hard"
"insufficient breath"
"less of a problem since the rehearsal venue was changed"
"it's getting very foggy in here"
Evidence that Pitch Drifts
"I was a choir boy in New College, Oxford, and for two years we had no organ as it was being rebuilt, so sang every single day *a cappella*. Very often, on a Friday when it was snowy outside and everyone was tired, we used to have intonation [pitch] problems and the piece would begin in E flat and end down a semitone. I remember Sir David Lumsden getting rather cross about this and deciding he would try initially to sing all the pieces in E and A, a semitone higher than they looked, and interestingly the intonation stayed. Now the question was why did it stay and I still can't tell you? But I think because it felt brighter, because we'd been told it was higher and because it required a great deal more connection of our diaphragm and our lungs to our vocal chords; because it was higher and a bit more effort we probably worked harder, brightened the sound and the pitch stayed."
Simon Halsey, Director of the CBSO Chorus, speaking in 'Key matters', BBC Radio 4, 27th October 2012
Art installation: Graham Mills *This Land is Our Land (2007)*
Purchased by the OU Artwork Group in 2008
How does the voice work?
velum
vocal tract
vocal folds
trachea
lungs
1.
2.
3.
radiated spectrum
vocal tract frequency curve formants
glottal voice source spectrum
waveform
frequency
time
Diagram from OU module *The Technology of Music* (TA212) Block 3:2
1. A stream of air from the lungs causes the vocal folds to vibrate generating a sound at a certain frequency. We can change this frequency by varying the length, tension and vibrating mass of our vocal folds. Because of the non-linear shape of the waveform it is rich in harmonics.
2. Resonance in the vocal tract causes modification of these harmonics. Certain frequencies, known as formant frequencies, are amplified.
3. The jaw, tongue, mouth and lips modify the shape of the vocal tract. This modifies the formant frequencies to make the sounds we hear as speech or song, as shown in the left diagram.
Findings from the pilot survey
All five choirs in the pilot survey were similar in terms of age, formation and types of music performed, so the outcomes are similar. However, the fact that all the directors of these choirs had different opinions as to why pitch drift occurs strengthens the case for a national survey to try to achieve some agreement as to which possible reasons require detailed investigation through carefully designed experimentation. It is proposed that trial experiments involving a self-selected choral ensemble will be taking place to take measurements and obtain some initial datasets.
One interesting finding was that Choir 1 which, as shown in the chart, sings mostly *a cappella* music, was the only choir to audition singers. However, their choral director still reported problems maintaining pitch.
Choir
5
4
3
2
1
0% 20% 40% 60% 80% 100%
Percentage of music sung *a cappella*

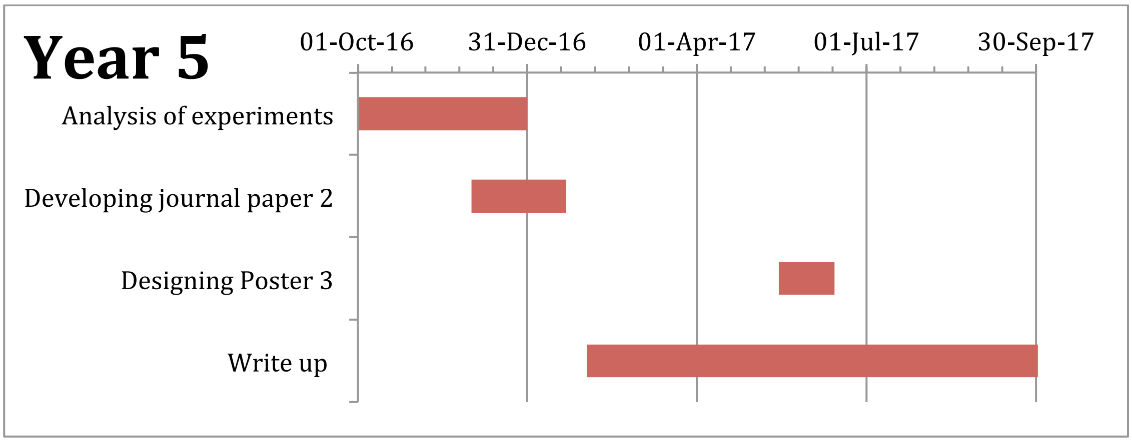
Appendix 4 Research plan

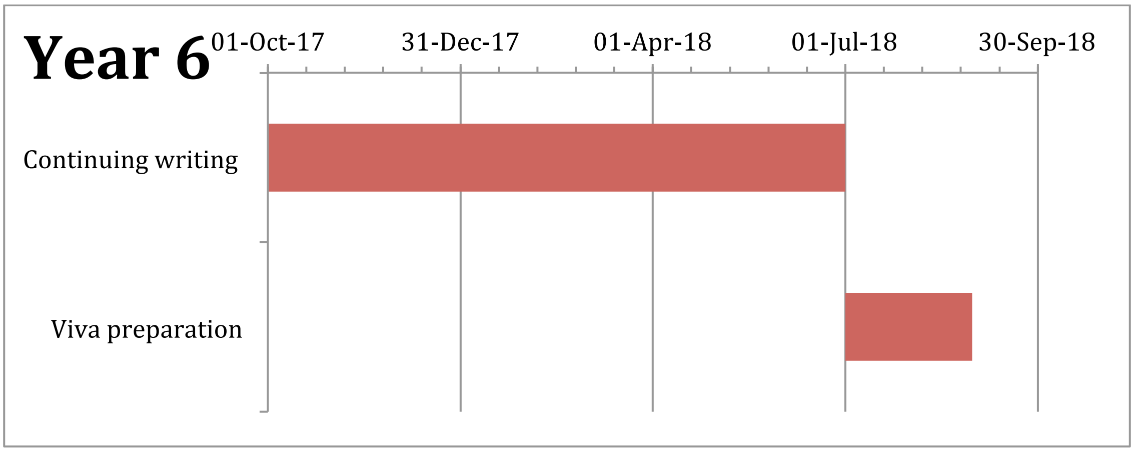







Year 4
01-Oct-15
31-Dec-15
31-Mar-16
30-Jun-16
29-Sep-16
Revsion of experiments
Attending conference
Experiments with choirs 2
Analysis of exeperiments 2


Year 5
01-Oct-16
31-Dec-16
01-Apr-17
01-Jul-17
30-Sep-17
Analysis of experiments
Developing journal paper 2
Designing Poster 3
Write up


Year 6
01-Oct-17
31-Dec-17
01-Apr-18
01-Jul-18
30-Sep-18
Continuing writing
Viva preparation

Appendix 5 Documentation for the experiments

PhD Research Project

Pitch drift in *a cappella* choral singing

Extended experiments with choirs

Richard Seaton
Open University PhD Student
pitch-drift@open.ac.uk

Table of contents

1 Outline methods

These experiments are to monitor for any pitch drift in two songs performed at each rehearsal over an extended period and compare the results against environmental, attendance and other data.

1.1 Recording experiment

1.1.1 Equipment

- Sony IC Recorder ICD-PX333
- Sheet music for the two test pieces
- Writable CD ROM

1.1.2 Details

Two short pieces of music (no more than 5 minutes in total) will be sung and recorded. The two works will be a specially composed *Pitch drift test piece* by Dr Dennis Pim and a song chosen for your choir.

1.2 Environment experiment

1.2.1 Equipment

- Precision Gold Model: N09AQ Multi-function Environment Meter
- Environmental data log sheet

1.2.2 Details

Measurements of temperature and humidity will be taken at each rehearsal. Sound and light levels will be measured as necessary. All measurements will be recorded on the log sheet. Atmospheric pressure will be recorded by the research team using information supplied by the Met Office and the National Physical Laboratory

1.3 Choir experiment

1.3.1 Equipment

- Choral director's notes
- Attendance register

1.3.2 Details

A form completed by the choral director after each rehearsal. Register of attendance completed for each rehearsal.

2 Detailed methods

2.1 Making recordings of the choir

The aim of making recordings of your choir week-by-week over twenty weeks is to discover if pitch variations occur more often some weeks than others. The recordings will be compared with environmental, attendance and other data to see if there is any correlation between pitch drift and changes in the data. The recordings you make will be of your choir singing two pieces, a test piece specially written by Dr Dennis Pim and a song chosen for your choir. Both pieces should take no more than five minutes to sing after initial note learning during the first rehearsal. Once learned though please do not practice the pieces before making the recordings, although you may record the choir singing the piece more than once if you wish. The important point regarding these recordings is to ensure they are made every time the choir meets in its usual venue and at the same time within each rehearsal. If at all possible make the recordings half way though your rehearsal as this may ensure the choir is warmed-up and the majority of singers for that week have arrived. Please only make the recordings in your usual rehearsal venue with the recorder in the same position each time you meet.

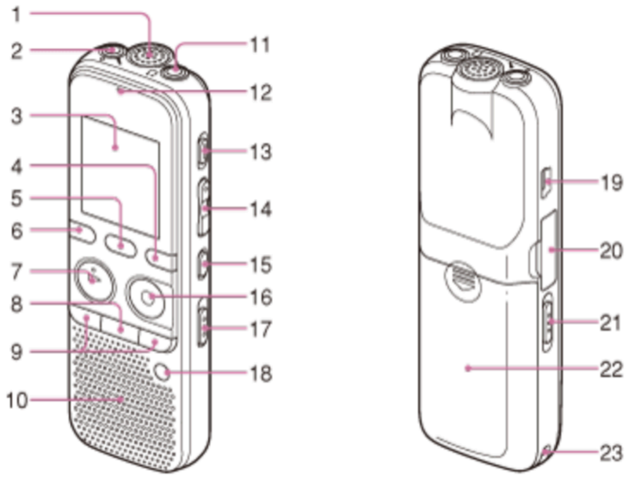
Recordings of the complete rehearsal are not necessary. However, if you find a particular piece you are rehearsing varies in pitch week by week it would be very useful to include recordings. If this is the case please make a note on the environment log sheet. All recordings and data will only be used for this research and any references to recordings will be anonymous.

The Sony IC Recorder ICD-PX333 has been chosen as being suitable in terms both of sound quality, despite only recoding in mono, and ease of use (hopefully). It is fitted with an 8GB memory card which allows approximately 90 hours of recording, sufficient for the complete experimental period even if you record extra pieces.

The recorder is supplied preconfigured but should changes be necessary the operating instructions are supplied. However, the necessary operations are included on subsequent pages.

If you have any problems or concerns please contact the research team by email at the address given on page 15. This mailbox is regularly monitored by members of the team.

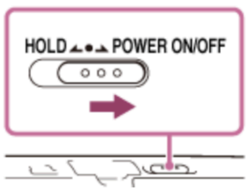
2.1.1 Parts and controls of the Sony IC Recorder ICD-PX333



1. Built-in microphone.
2. Microphone jack.
3. Display Window.
4. DISP/MENU button.
5. SCENE button.
6. FOLDER button.
7. ▶PLAY/STOP•ENTER button.
8. ■ (stop) button.
9. -|◀◀ (review/fast backward), ▶▶|+ (cue/fast forward) buttons.
10. Loudspeaker.
11. Headphone jack.
12. Operation indicator.
13. ERASE button.
14. VOL –/+ (volume) button.
15. A-B (repeat) A-B Button.
16. ●REC/PAUSE button.
17. NOISE CUT switch.
18. T_MARK (track mark) button.
19. USB connector.
20. microSD memory card slot.
21. HOLD•POWER ON/OFF switch.
22. Battery compartment.
23. Strap hole (strap not supplied).

2.1.2 Switching the recorder on and off

To switch on the recorder slide the HOLD•POWER ON/OFF switch (22) on the left hand side of the recorder in the POWER ON/OFF direction as shown below for more than one second.



To switch off the recorder move and hold the POWER ON/OFF switch in the POWER ON/OFF direction until “Power Off” is displayed. Note that if left unused, i.e. not recording or playing back, the recorder will power down after 10 minutes. The HOLD position is used to avoid unintended operations.

2.1.3 Taking a recording

Switching on the recorder will give a display similar to the one shown below. The recorder is in the stop mode. The date and time are important as they are used as part of the file name. To check the date and time press the DISP button (4) twice. The current date and time will be displayed at the top of the screen.

Before you start recording please check the battery indicator in the bottom right of the display to ensure more than one bar is displayed. If only one bar is displayed there should be enough power for a five minute recording but replace the battery as soon as possible. Details are shown on page 8.

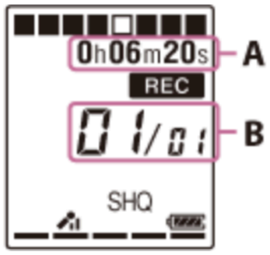
Use FOLDER01 for all recordings of your choir. A folder can hold up to 199 sequentially numbered files, which will be sufficient for the whole experiment. Files are numbered sequentially from 1 to 199 when accessed on the recorder. However, the recordings are named with the date and number, e.g. “150522_001.MP3”, on the memory card where “150522” represents 22nd May 2015, the “001” the first recording that day and “MP3” the file format.

Place the recorder in a convenient position for your recordings with the microphone (1) pointing towards the choir. Be sure to use the same position each week.

Press the ●REC/PAUSE button (found on the right below the display with the red dot in the centre) once. The operation indicator (12) flashes orange briefly, then lights in red indicating recording has started. A new file will be

6

recorded automatically as the last file in the current folder, i.e. FOLDER01. The display when recording is shown below.

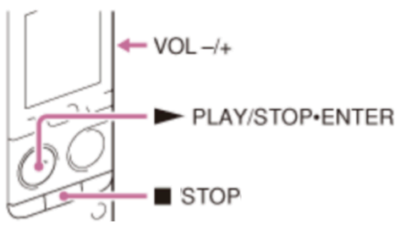


The elapsed time of the current recording (A) is shown along with the current file number (left) and the total number of files (right) in the folder (B). The blank square at the top of the display moves to the right every second along with the elapsed time giving a visual indication that a recording is in progress.

To finish recording press the ▶PLAY/STOP•ENTER button (7). The display will indicate briefly that it is "Accessing…" while it saves the file to memory and then returns to the stop mode window. The file will be played back immediately. If you want to finish the recording *without* playing back immediately press the ■ (stop) button (8) shown below. This could be useful during the rehearsal.

2.1.4 Playing back a recording

The recorder is fitted with a small internal speaker (10) so you can listen to the sound. Alternatively use headphones plugged into the headphone socket (11). To play the latest recording press the ▶PLAY/STOP•ENTER button (7) and adjust the sound level by pressing the VOL -/+ button (14) on the right-hand side. Ensure the volume is not too high if using headphones. If the sound is distorted or too quiet then change the microphone sensitivity (initially set to medium) as shown on page 11. Press ▶PLAY/STOP•ENTER button (7) to stop playback. Press it again to resume playing back from where it stopped. During playing back the operation indicator (12) is green.



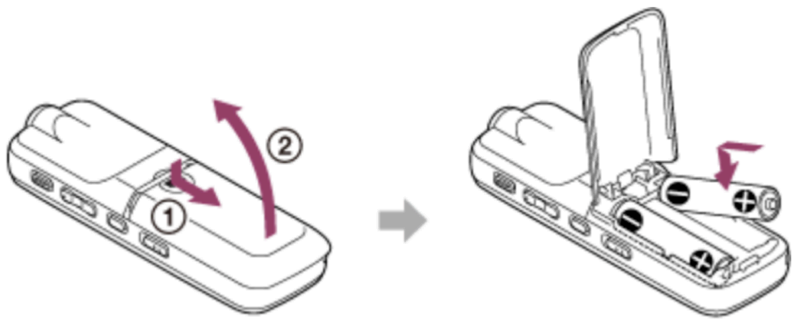
7

If you want to playback another recording select the recording number you want by using the appropriate double arrow button **-|◀◀** or **▶▶|+** (9). Press the ▶PLAY/STOP•ENTER button to play the recording. Note that you can use the double arrow buttons to play other recordings without stopping the previous one.

2.1.5 Replacing the battery

The recorder battery uses two AAA (LR03) alkaline cells which should allow up to 60 hours of recording. The state of the battery is shown on the display in the bottom right-hand corner. Replace the two cells (which are supplied) when a single bar is showing in the indicator. Contact the research team, using the email address on page 15, for additional AAA cells.

To change the battery refer to the diagram below. Switch off the recorder, open the cover on the rear by sliding it gently in the direction of the arrow (1) and then lifting it up (2). Note that it remains attached to the recorder. Remove both old cells and fit replacements both with the positive (+) terminals to the bottom of the unit (this is slightly unusual placement). Close the cover and gently slide forward to lock in place. Safely dispose of the old cells as directed by your local authority.



If the recorder is without power for more than a minute or two, or if the battery is flat, you will be prompted to re-enter the date and time when you switch on. Following a prompt to "Set Date and Time" you will see the display shown below.

Use the appropriate double arrow button **-|◀◀** or **▶▶|+** to set the year (last two digits) and then press the ▶PLAY/STOP•ENTER button (7) to confirm

8

the year and move on to the month. Repeat for month, day, hour and minutes. Once completed “Executing…” is displayed briefly followed by the stop mode window.

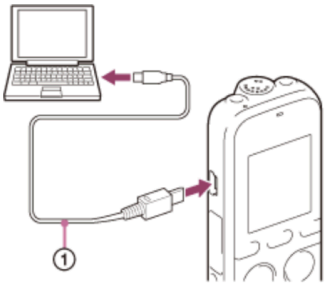
Warning: Please do not press the ▶PLAY/STOP•ENTER button until you have set the correct date and time as you cannot then correct any mistake without either removing the battery for five minutes or using the menu and submenus to navigate to the date and time menu. Refer to the Sony Help Guide for instructions on setting the clock using the menu and submenus .

2.1.6 Backing up and returning recordings

If you are able to connect the recorder to a computer please copy the recordings to the computer’s hard disk for security. Please don’t remove any files from the recorder. If possible also send each week’s recording to the research mailbox using the email address on page 15. A writable CD ROM is provided for returning the recordings under separate cover at the end of the 20 week period even if you have sent recordings after each rehearsal, see page 14.

2.1.7 Connecting to a computer

Connect the recorder to a computer using the supplied USB connecting cable (1) shown below. There is no need to switch on the recorder before connecting it to the computer. After a few moments “Connecting” will be displayed on the recorder and the indicator will flash green briefly.



2.1.8 Using a Windows® computer

If you use a Windows® computer (PC) you will see a message on the computer’s screen whilst the device driver is loaded. Eventually you should be asked either to open memory devices or if not you should go to “My computer” or “Computer”. You will see two memory devices, “IC RECORDER” and “MEMORY CARD”, as shown below. “IC RECORDER” device stores some editing software and a copy of the manual as well as

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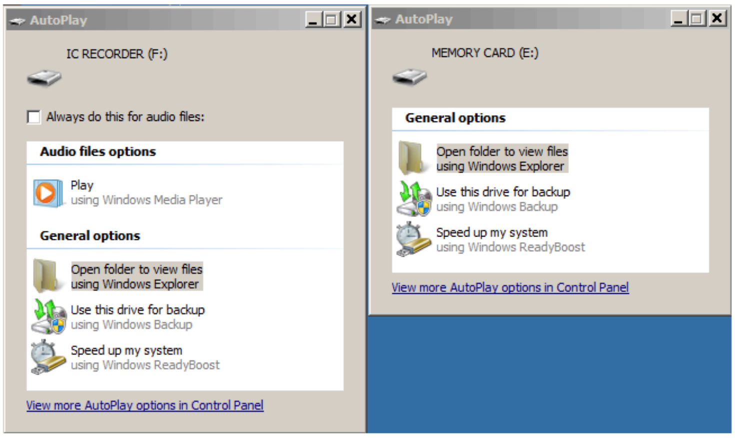
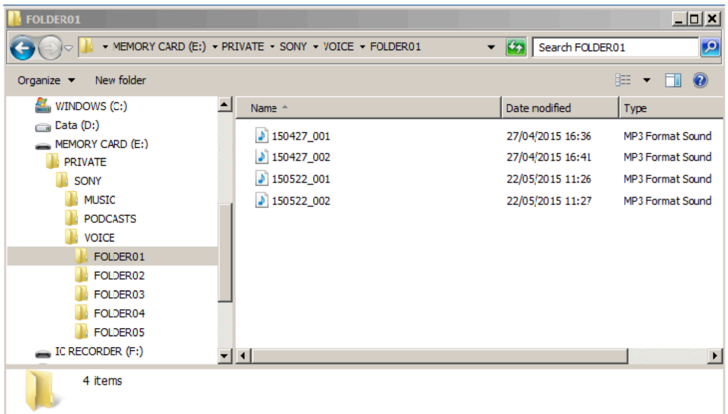
additional folders – the contents of this folder should not be altered. “MEMORY CARD” stores the recordings of the choir.



Open “MEMORY CARD” and navigate to “PRIVATE/SONY/VOICE/ FOLDER01” to display the list of the recordings, shown below. Copy any new ones to a suitable place on your computer’s hard disk. Please don’t delete any previous recordings.



Finally close the windows and eject the media before disconnecting the recorder, otherwise the recorder files may become damaged or unplayable.

First left-click on the taskbar USB icon (arrowed in the diagram below), then left-click “Eject IC RECORDER” or “Safely remove USB Mass Storage Device” depending on your version of Windows. You can then safely unplug the cable from the computer and recorder.

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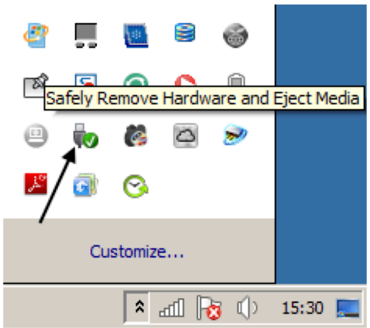

For more details on connecting and disconnecting USB devices refer to the operating instructions supplied with your computer.

2.1.9 Using an Apple Mac® Computer

If you use an Apple Mac® computer, plugging in the recorder displays two memory devices, “IC RECORDER” and “MEMORY CARD”, on the desktop. They can be opened in the Finder and treated as any normal memory device, but do not change the contents of the “IC RECORDER” folder as this device stores some editing software and a copy of the manual as well as additional folders. Open the “MEMORY CARD” device and navigate to “private/SONY/VOICE/FOLDER01” to display the list of recordings and then copy the required ones to a suitable place on your computer’s hard disk. Eject both ICRECORDER and MEMORY CARD devices before unplugging the recorder.

For more details on connecting and disconnecting USB devices refer to the operating instructions supplied with your computer.

2.1.10 Recorder settings

The following settings are used:

- Folder: FOLDER01.
- Memory: MEMORY CARD (8 GB).
- Noise cut: OFF.
- Scene: Lecture (SHQ record mode, medium microphone sensitivity).

2.1.11 Reference

Sony IC Recorder ICD-PX333 Help Guide © 2013 Sony Corporation.

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2.2 Making environmental measurements

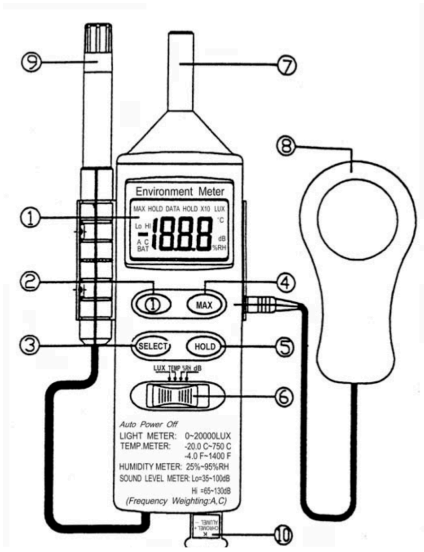
The research mainly aims to determine if changes in temperature, humidity and atmospheric pressure can affect a choir's ability to maintain pitch. However, it will be useful to know whether the light and sound levels also have an affect.

Measurements of temperature and humidity should be made at each rehearsal and the results recorded on the supplied log sheet. These measurements should be taken when the recording is made. Note that the research team are responsible for recording atmospheric pressure readings from data supplied by the Met Office. Light and sound levels need only be made once but if changes are noticed please take a new reading and note on the log sheet accordingly.

2.2.1 Parts and controls of the Multi-Function Environment Meter

The environment meter is used for taking the measurements. As it is unable to store readings a log sheet is provided which should be completed at each rehearsal. (A computer spreadsheet version is also available.)

To make measurements place the environment meter in a convenient position with the microphone (7) pointing towards the choir. Please use the same position each week to ensure consistency of readings. The temperature and humidity probe (9) may remain clipped to the meter.



1. LCD display.
2. POWER, press to switch on and off.
3. SELECT functions & ranges.
4. MAX displays maximum reading.
5. HOLD keeps current reading.
6. Function selector.
7. Sound level sensor (mike).
8. Light sensor and black cover (supplied as a separate unit).
9. Temperature and humidity sensor.
10. Socket for external temperature probe (not supplied).

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2.2.2 Taking measurements

Allow at least 10 minutes between setting up and taking any readings to allow the meter's sensors to stabilize (no need to switch on for this to happen). Take temperature and humidity readings when you record the singing at every rehearsal. The sound and light levels need only be taken once unless you suspect a change, due say to increased background noise because of heating or a change from natural to artificial light.

2.2.3 Temperature and humidity (weekly)

1. Slide the Function selector (6) to "TEMP".
2. Switch on the meter by pressing the "POWER" button (2).
3. Allow a few moments for the reading to stabilize and then record the temperature level from the LCD display (1) on the log sheet.
4. Slide the Function selector (6) to "%RH".
5. Again, allow the reading to stabilize and then record the relative humidity reading on the log sheet.
6. Switch off the meter by pressing the "POWER" button (2).

2.2.4 Sound level (one-off unless conditions change)

Sound level measurements are to provide an indication of the sound pressure level (SPL) of both the rehearsal venue background sound and that generated by the choir singing at maximum volume. Two sound level measurements should be taken just before making a recording early on in the experiment. The choral director should firstly ask the choir be as quiet as possible for a few seconds to enable a background sound level reading to be taken. Then the choir should be asked to sing a very loud chord, to the vowel 'E', using notes as follows:

- SATB choir: F5, A4, C4 and F3;
- TTBB choir: F4, C4, A3 and F3;
- SSA(A) choir: F5, A4, C4 and (F3).

1. Set the Function selector (6) to "dB".
2. Switch on meter by pressing "POWER" button (2).
3. Check that "Lo A" is displayed on left-hand side of the LCD display (1). If not then use the SELECT button to scroll around to this setting.
4. Indicate to the choral director you are ready to make measurements.
5. When the choir is quiet note the background sound level reading.
6. Press "MAX" (4) once to hold highest sound level.
7. Ask the choir to sing loudly as detailed above.
8. Note the sound level reading from the LCD display on the log sheet.
9. Switch off the meter.

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2.2.5 Light level (one-off unless conditions change)
It may be necessary to move the to a position which represents the light level where the singers are positioned before taking the readings.

1. Remove the black cover from the external light sensor (8) and plug in the sensor to the jack socket on the right-hand side of the meter.
2. Set the Function selector (6) to “LUX”.
3. Switch on meter by pressing “POWER” button (2).
4. If the LCD display (1) shows “1” then the meter is too sensitive. Reduce the sensitivity by pressing the “SELECT” button (3). Each time the button is pressed the sensitivity is reduced by a factor of 10. After the 4th setting the most sensitive range repeated. Choose the most sensitive setting that does not cause “1” to be displayed.
5. Note the light level shown on the LCD display on the log sheet.
6. Switch off the meter.

2.2.6 Replacing the battery
If the meter fails to switch on, or if “BAT” appears on the display, slide open the battery cover at the base of the rear of the meter. Replace the old battery and refit the cover. Contact the research team, using the email address below, for a replacement. Safely dispose of the old battery as directed by your local authority.

2.2.7 Reference
Precision Gold Instruction Manual Model N09AQ © Maplin Electronics Ltd.

2.3 Choir experiment

2.3.1 Choral director’s summary
A brief report by the choral director of choir’s general performance and an estimation of pitch drift in the rehearsal should be completed each week.

2.3.2 Attendance records
A copy of a register of attendance for each rehearsal should be returned at the end of the 20 week experiment. If not done so already the data will be anonymised by the research team. No singers’ names will be used but the choir named may be used if agreement is given by the members.

3 Returning the experimental equipment

Please contact the research team, using the email address below, to make arrangements to return the experimental equipment to the Open University.

4 Contacts

Please contact the research team at pitch-drift@open.ac.uk if you have questions, problems or need spare batteries, etc.

5 Notes

Appendix 6 Specification for the environment meter

<table>
<tr><th colspan="4">Technical Details</th></tr>
<tr><th>Function</th><th>Measurement Range</th><th>Resolution</th><th>Accuracy</th></tr>
<tr><td rowspan="4">Sound</td><td>A LO (low) - Weighting: 35-100 dB</td><td rowspan="4">0.1 dB</td><td rowspan="4">±3.5 dB at 94 dB, 1KHZ sine wave</td></tr>
<tr><td>A HI (High) - Weighting: 65-130 dB</td></tr>
<tr><td>C LO (low) - Weighting: 35-100 dB</td></tr>
<tr><td>C HI (High) - Weighting: 65-130 dB</td></tr>
<tr><td>Humidity</td><td>25% to 95% RH</td><td>0.1% RH, 0.1°C</td><td>±5% RH (at 25°C, 35%~95% RH)</td></tr>
<tr><td rowspan="2">Light</td><td rowspan="2">20, 200, 2000, 20000 Lux</td><td>1 Lux (0 to 2000 Lux)</td><td rowspan="2">±5% of reading + 10 digits</td></tr>
<tr><td>10 Lux (2000 to 20000 Lux)</td></tr>
<tr><td rowspan="2">Temperature (Type K)</td><td rowspan="2">-20°C to +750°C (-4°F to +1382°F)</td><td rowspan="2">0.1 °C/1°C, 0.1 °F/1°F</td><td>±3% reading ±2°C (at -20°C~+200°C)</td></tr>
<tr><td>±3.5% reading ±2°C (at -20°C~+750°C)</td></tr>
<tr><td>Microphone</td><td colspan="3">Electric condenser microphone</td></tr>
<tr><td>Photo Detector</td><td colspan="3">Long life silicon photo diode with filter</td></tr>
<tr><td>Storage Temperature</td><td colspan="3">-10°C to +60°C (+14°F to +140°F)</td></tr>
<tr><td>Storage Humidity</td><td colspan="3">< 80% RH</td></tr>
<tr><td>Power</td><td colspan="3">1 x 9V battery (supplied)</td></tr>
<tr><td>Dimensions</td><td colspan="3">251mm (H) x 63.8mm (W) x 40mm (D)</td></tr>
<tr><td>Weight</td><td colspan="3">250g</td></tr>
</table>

Appendix 7 Environmental data log sheet

MeasurementsLog.xlsx

Week number	*Date*	*Start time*	*Temperature (°C)*	*Humidity (hPa)*	*Light level (Lux)†*	*Sound level (dBA)†*		*Air pressure (hPa)**	*Remarks*
						Background	*Choir*		
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
15									
16									
17									
18									
19									
20									

*To be completed by R Seaton

†Only measure once unless significant changes are noticed

Appendix 8 Test Piece Scores

A8.1 Four-part SATB version

A8.2 Four-part version for lower voices

PhD Research: Pitch drift in a cappella choral singing
Richard Seaton, The Open University

Pitch-drift test piece

(lower voices)

Dennis Pim
March 2015

Appendix 9 List of chosen songs

Chosen song	Composer	Dates
Adam lay ybounden	Boris Ord	1887–1961
Can you feel the love tonight	Elton John (arr. June Dale)	1947–
Ego sum panis vivus	Giovanni Palestrina	1525–1594
God so loved the world	Sir John Stainer	1840–1901
Heraclitus	Sir Charles Villiers Stanford	1852–1924
Locus iste	Anton Bruckner	1824–1896

Appendix 10 Post rehearsal questionnaire for musical directors

Choral Director's notes on the rehearsal for <insert choir name>

Name	<insert MD name>	Date	
General opinion of performance*			
Comments: (continue overleaf)			
Estimation of maintenance of pitch*			
Comments: (continue overleaf)**			

*Please enter most appropriate letter: (A) Excellent, (B) Above average, (C) Average, (D) Below average, (E) Poor.

** Please comment here if any "key" singers were not attending and whether this made a difference (no names please but mention the part).

Appendix 11 *MatLab*® code for generating tones for the Pitch Discrimination Survey


```
% prepare sample sound
sf = 44100;                                  % sampling frequency (Hz)
n = floor(sf * 2.0);                         % length of sound (s)
freq = 440.0;                                % required frequency (Hz)
t = ((1:n) / sf);                            % sound data preparation
s = sin(2 * pi *  freq * t);                 % pure tone

% save as wav file
bit = 16;                                    % set bits/sample (8 or 16)
byte = bit / 8;                              % set bytes/sample
[ch, dl] = size(s);                          % size of data
% file header
fid = fopen('A4+cent0.wav', 'wb');           % filename (.wav)
fwrite(fid, hex2dec('52'), 'uchar');         % 'R' in ASCII code
fwrite(fid, hex2dec('49'), 'uchar');         % 'I' in ASCII code
fwrite(fid, hex2dec('46'), 'uchar');         % 'F' in ASCII code
fwrite(fid, hex2dec('46'), 'uchar');         % 'F' in ASCII code
fwrite(fid, dl * ch * byte + 36, 'ulong');   % file size from next to EOF
fwrite(fid, hex2dec('57'), 'uchar');         % 'W' in ASCII code
fwrite(fid, hex2dec('41'), 'uchar');         % 'A' in ASCII code
fwrite(fid, hex2dec('56'), 'uchar');         % 'V' in ASCII code
fwrite(fid, hex2dec('45'), 'uchar');         % 'E' in ASCII code
fwrite(fid, hex2dec('66'), 'uchar');         % 'f' in ASCII code
fwrite(fid, hex2dec('6D'), 'uchar');         % 'm' in ASCII code
fwrite(fid, hex2dec('74'), 'uchar');         % 't' in ASCII code
fwrite(fid, hex2dec('20'), 'uchar');         % ' ' in ASCII code
fwrite(fid, bit, 'ulong');                   % quantization bit rate
fwrite(fid, 1, 'ushort');
fwrite(fid, ch, 'ushort');                   % # of channels
fwrite(fid, sf, 'ulong');                    % sample frequency
fwrite(fid, sf * ch * byte, 'ulong');        % data speed
fwrite(fid, ch * byte, 'ushort');            % block size
fwrite(fid, bit, 'ushort');                  % bit rate
fwrite(fid, hex2dec('64'), 'uchar');         % 'd' in ASCII code
fwrite(fid, hex2dec('61'), 'uchar');         % 'a' in ASCII code
fwrite(fid, hex2dec('74'), 'uchar');         % 't' in ASCII code
fwrite(fid, hex2dec('61'), 'uchar');         % 'a' in ASCII code
fwrite(fid, dl * ch * byte, 'ulong');        % sound data size (byte)
% file data
s=s-min(s(:));                               % minimum value = 0
s=s/max(s(:))*(2^bit)-2^(bit-1);             % -2^(bit-1) - 2^(bit-1)
s=int16(s);
for y = 1:dl
    for x = 1:ch
        fwrite(fid, s(x, y), 'short');       % sound data
    end
end
fclose(fid);
%end
```

Appendix 12 Letter introducing the Pitch Discrimination Survey

The Open University

PhD Research: Pitch drift in a cappella choral singing
Richard Seaton, The Open University

Online survey of singers from <insert name of choir here>

Aim:

To gain an appreciation of the ability of singers from <choir name> to discriminate between two notes which differ slightly in pitch.

Details:

Please take part in this survey which is a really important aspect of my research. You won't be asked for any personal details except (optionally) for your voice part. All data collected are anonymous and will only be used in my research. Unfortunately, due to the need for anonymity, you will not receive any results. You may take part in the survey, which will take only a few minutes, at any time during the period of the experiment.

Taking the survey:

To take part you will need either a computer or a smartphone or tablet attached to the internet and either a reasonable loudspeaker or headphones to listen to pairs of tones. To take the survey go to:

http://tinyurl.com/xxxxxx or use the QR link opposite.

If you cannot access the survey check that this address has not been changed by your spelling checker or application of predictive text.

Enter the password "nnnnnnn" (all lower-case without quotes). You will then see an explanation of pitch discrimination and instructions for taking the survey.

Contact details:

If you have any problems whatsoever with the survey please try again on a different occasion and, if that doesn't work, contact me at pitch-drift@open.ac.uk .

You can find out more about my research at:

http://mcs.open.ac.uk/acoustics/pitchdrift/index.php

Many thanks,

Richard

Richard Seaton, PhD Student at The Open University.

Appendix 13 Experiment kit handover letter

PhD Research Project

Extended experiments with choirs

Contents List

1. Recording experiment:
   a. Sony IDC-PX333 fitted with an 8GB memory card
   b. USB lead
   c. Writable CD-ROM
   d. Instructions
   e. 2 spare AAA cells*
   f. Pitch-drift test piece*
   g. Additional song (optional)*

2. Environment experiment:
   a. Hand-held meter fitted with wind cover
   b. Light level sensor
   c. *Measurements Log* sheets (if not returned by email)
   d. Instructions
   e. Spare PP3 9V battery*

3. Choir experiment:
   a. 20 *Choral Director's Notes*
   b. Attendance register (to be discussed at first meeting)
   c. Clipboard*

4. Extended experiments with choirs *

5. Instructions for Pitch Discrimination Survey*

*Need not be returned at the end of the experiments.

On behalf of <choir name> I agree to return the non-starred equipment listed above by arrangement with Richard Seaton the end of the experimental period.

Name ………………………………………………

Signature ………………………………………….. Date…………………………….

Appendix 14 Pitch drift ratings for all choirs

Choir A

Test Piece																		
Rehearsal	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Quant	G	G	P	G	G	G	G	G	G	P	P	P	G	P	G	G	G	G
Qual1	G	G	P	G	G	G	G	G	G	P	G	P	G	P	G	G	G	G
Qual2	G	P	G	G	G	G	P	P	G	P	G	G	G	G	G	G	G	G
Pitch drift rating	**G**	**G**	**P**	**G**	**G**	**G**	**G**	**G**	**G**	**P**	**G**	**P**	**G**	**P**	**G**	**G**	**G**	**G**
Chosen song																		
Rehearsal	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Quant rating	G	G	G	P	G	P	G	G	G	P	P	P	G	G	P	G	P	P
Qual1 rating	G	G	G	P	G	P	G	G	G	G	P	P	G	G	G	G	P	P
Qual2 rating	G	G	G	P	G	P	G	G	G	P	G	P	G	G	G	G	P	P
Pitch drift rating	**G**	**G**	**G**	**P**	**G**	**P**	**G**	**G**	**G**	**P**	**P**	**P**	**G**	**G**	**G**	**G**	**P**	**P**

Choir B

Test Piece																				
Rehearsal	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Quant	G	P	G	G	P	G	P	P	G	G	P	P	G	G	P	G	G	G	P	G
Qual1	G	G	G	P	G	G	G	P	P	G	G	G	G	P	G	P	P	G	G	G
Qual2	P	G	G	G	G	G	G	P	G	G	G	G	G	G	G	G	G	G	G	G
Pitch drift rating	**G**	**G**	**G**	**G**	**G**	**G**	**G**	**P**	**G**	**G**	**G**	**G**	**G**	**G**	**G**	**G**	**G**	**G**	**G**	**G**
Chosen song																				
Rehearsal	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Quant rating	G	G	G	P	G	G	G	G	G	G	G	P	G	G	G	G	P	G	G	G
Qual1 rating	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
Qual2 rating	G	G	G	P	G	P	G	G	G	G	G	G	G	G	G	G	G	G	G	G
Pitch drift rating	**G**	**G**	**G**	**P**	**G**	**G**	**G**	**G**	**G**	**G**	**G**	**G**	**G**	**G**	**G**	**G**	**G**	**G**	**G**	**G**

Choir C

Test Piece																	
Rehearsal	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Quant	G	G	P	G	P	P	G	G	P	G	G	G	G	G	P	G	G
Qual1	G	P	P	P	G	G	G	G	P	P	P	G	G	G	P	P	G
Qual2	G	G	G	G	G	G	G	G	P	P	G	G	G	G	G	G	G
Pitch drift rating	**G**	**G**	**P**	**G**	**G**	**G**	**G**	**G**	**P**	**P**	**G**	**G**	**G**	**G**	**P**	**G**	**G**
Chosen song																	
Rehearsal	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Quant rating	G	G	G	P	G	P	G	G	P	G	P	G	G	G	G	G	P
Qual1 rating	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
Qual2 rating	G	G	P	G	G	P	P	G	P	G	P	G	G	G	G	G	G
Pitch drift rating	**G**	**G**	**G**	**G**	**G**	**P**	**G**	**G**	**P**	**G**	**P**	**G**	**G**	**G**	**G**	**G**	**G**

Choir D

Test Piece																				
Rehearsal	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Quant	G	G	G	P	G	P	P	P	G	G	G	G	G	G	P	G	P	P	G	P
Qual1	G	G	G	P	G	P	P	P	G	G	G	P	G	G	P	G	P	P	G	P
Qual2	G	P	G	P	P	P	P	P	G	G	G	P	P	G	P	G	P	P	G	P
Pitch drift rating	**G**	**G**	**G**	**P**	**G**	**P**	**P**	**P**	**G**	**G**	**G**	**P**	**G**	**G**	**P**	**G**	**P**	**P**	**G**	**P**
Chosen song																				
Rehearsal	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Quant rating	G	G	G	P	P	P	P	P	G	G	G	P	G	G	P	G	P	P	P	G
Qual1 rating	G	G	G	P	P	P	P	P	P	G	G	P	G	G	G	P	P	P	P	P
Qual2 rating	G	G	G	P	P	P	G	P	G	G	G	P	G	G	G	G	G	P	P	P
Pitch drift rating	**G**	**G**	**G**	**P**	**P**	**P**	**P**	**P**	**G**	**G**	**G**	**P**	**G**	**G**	**G**	**G**	**P**	**P**	**P**	**P**

Choir E

Test Piece																				
Rehearsal	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Quant	G	G	P	G	P	G	P	G	G	G	G	P	P	P	P	G	G	P	P	G
Qual1	G	G	P	G	P	P	G	G	G	P	P	P	P	P	P	P	P	P	P	G
Qual2	G	G	P	G	P	G	G	G	G	G	G	G	G	P	P	P	P	P	G	G
Pitch drift rating	**G**	**G**	**P**	**G**	**P**	**G**	**G**	**G**	**G**	**G**	**G**	**P**	**P**	**P**	**P**	**P**	**P**	**P**	**P**	**G**
Chosen song																				
Rehearsal	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Quant rating	G	G	P	G	P	G	P	P	G	P	G	P	G	P	P	P	P	G	P	G
Qual1 rating	G	G	G	G	P	G	P	G	P	P	G	P	G	P	G	P	P	G	P	P
Qual2 rating	G	P	P	G	P	P	P	P	P	P	G	P	G	P	G	P	P	G	P	G
Pitch drift rating	**G**	**G**	**P**	**G**	**P**	**G**	**P**	**P**	**P**	**P**	**G**	**P**	**G**	**P**	**G**	**P**	**P**	**G**	**P**	**G**

Choir F

Test Piece																				
Rehearsal	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Quant	G	G	G	G	G	G	G	P	P	P	P	G	G	P	P	P	P	P	P	P
Qual1	G	G	G	G	G	G	G	G	P	G	P	G	G	P	P	P	G	P	P	P
Qual2	G	G	G	G	G	G	G	G	P	G	P	G	G	P	P	P	G	P	G	G
Pitch drift rating	G	G	G	G	G	G	G	G	P	G	P	G	G	P	P	P	G	P	P	P
Chosen song																				
Rehearsal	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Quant rating	P	P	P	P	P	G	G	G	P	P	P	G	P	P	P	P	P	P	P	P
Qual1 rating	P	G	G	P	P	G	G	P	P	P	P	G	P	P	P	P	P	P	P	P
Qual2 rating	P	G	G	P	P	G	G	P	P	P	P	G	P	P	P	P	P	P	P	P
Pitch drift rating	P	G	G	P	P	G	G	P	P	P	P	G	P	P	P	P	P	P	P	P

Choir G

Test Piece																			
Rehearsal	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Quant	P	G	G	P	G	P	G	P	G	P	G	G	P	G	G	P	P	G	P
Qual1	G	G	P	P	G	P	G	G	P	G	G	G	P	G	G	G	P	G	G
Qual2	G	G	G	P	G	G	G	P	G	P	G	P	P	G	G	G	P	G	P
Pitch drift rating	G	G	G	P	G	P	G	P	G	P	G	G	P	G	G	G	P	G	P
Chosen song																			
Rehearsal	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Quant rating	G	G	P	P	P	G	P	G	G	P	P	P	P	P	P	P	G	G	P
Qual1 rating	G	G	P	P	P	G	P	G	G	P	P	P	P	P	G	P	G	G	P
Qual2 rating	G	G	P	P	P	G	P	G	G	P	P	P	P	P	P	P	G	G	P
Pitch drift rating	G	G	P	P	P	G	P	G	G	P	P	P	P	P	P	P	G	G	P

Choir H

Test Piece																				
Rehearsal	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Quant	P	G	G	G	P	P	G	P	G	P	G	P	P	G	P	G	G	G	P	P
Qual1	P	P	P	P	P	P	G	P	P	P	P	P	P	P	P	G	P	G	P	P
Qual2	G	G	G	P	G	G	G	P	G	P	G	P	P	G	G	G	P	G	P	G
Pitch drift rating	P	G	G	P	P	P	G	P	G	P	G	P	P	G	P	G	P	G	P	P
Chosen song																				
Rehearsal	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Quant rating	P	G	P	P	G	G	G	P	G	P	G	P	P	P	G	P	P	P	P	P
Qual1 rating	P	G	P	P	P	P	P	P	G	P	G	P	P	P	G	P	P	G	G	P
Qual2 rating	P	G	G	P	G	P	G	P	G	G	G	P	P	P	P	G	G	P	P	G
Pitch drift rating	P	G	P	P	G	P	G	P	G	P	G	P	P	P	G	P	P	P	P	P

Choir I

Test Piece																		
Rehearsal	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Quant	P	G	G	G	G	G	G	P	G	G	G	G	G	G	G	P	G	P
Qual1	G	G	P	G	G	G	P	G	P	G	G	G	G	G	G	G	G	P
Qual2	P	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
Pitch drift rating	P	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	P
Chosen song																		
Rehearsal	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Quant rating	G	P	G	G	G	G	G	G	G	P	G	G	G	G	G	P	G	G
Qual1 rating	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
Qual2 rating	G	P	G	G	G	G	G	G	G	G	P	G	G	G	P	P	G	G
Pitch drift rating	G	P	G	G	G	G	G	G	G	G	G	G	G	G	G	P	G	G

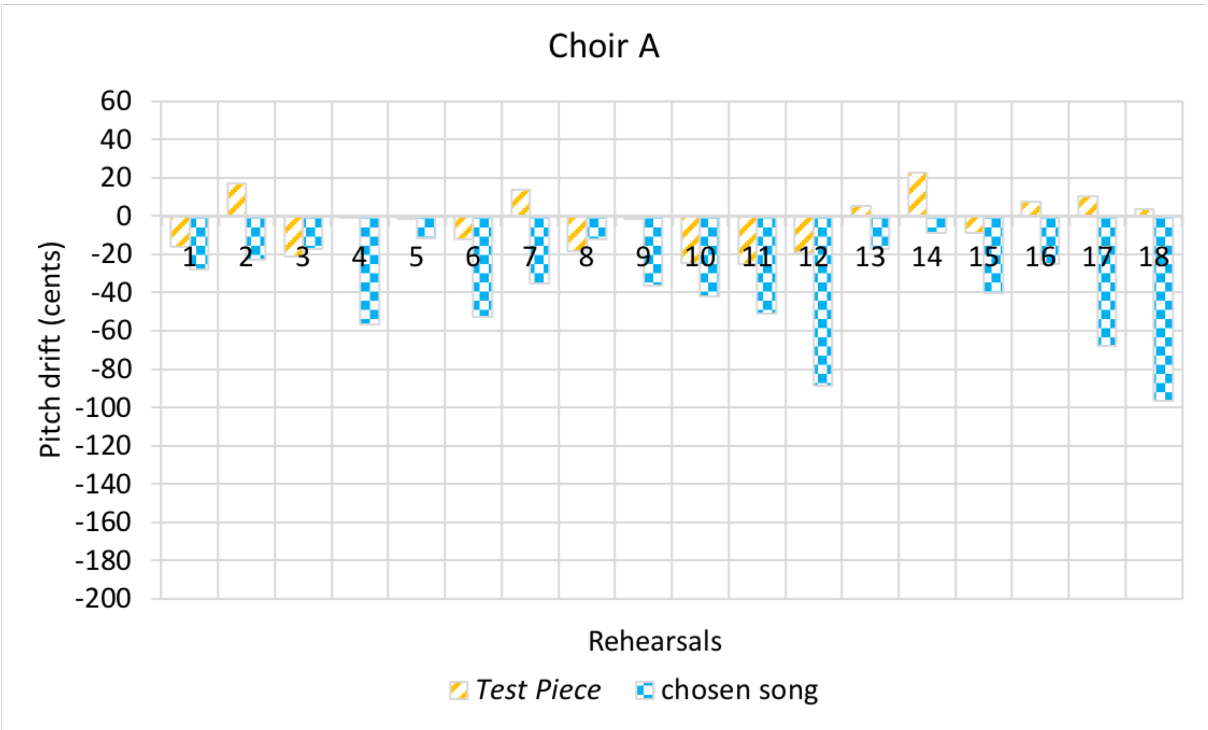
Choir J

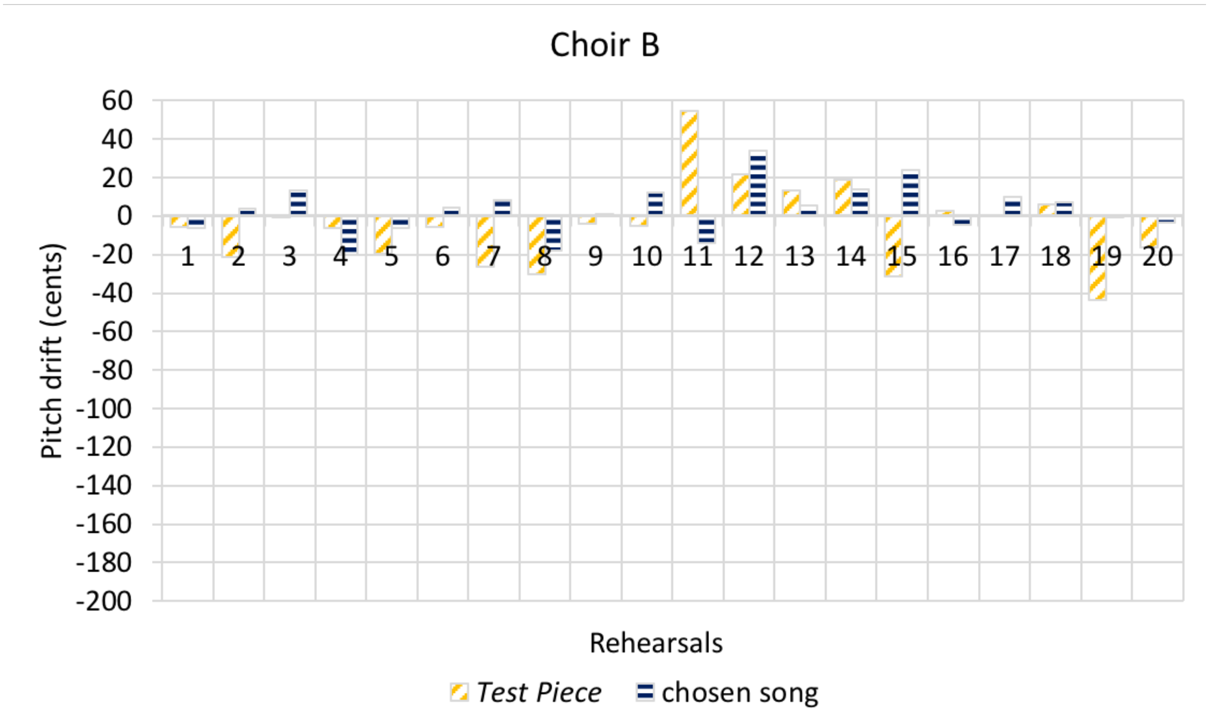
Test Piece												
Rehearsal	1	2	3	4	5	6	7	8	9	10	11	12
Quant	P	G	P	G	G	P	G	G	G	G	G	P
Qual1	P	G	P	P	G	P	G	G	G	G	G	G
Qual2	G	G	P	P	G	G	G	G	G	G	G	G
Pitch drift rating	P	G	P	P	G	P	G	G	G	G	G	G
Chosen song												
Rehearsal	1	2	3	4	5	6	7	8	9	10	11	12
Quant rating	P	G	G	G	G	P	G	P	G	G	P	G
Qual1 rating	P	G	G	G	G	P	G	P	G	G	G	G
Qual2 rating	P	G	G	G	P	P	G	P	P	G	P	P
Pitch drift rating	P	G	G	G	G	P	G	P	G	G	P	G

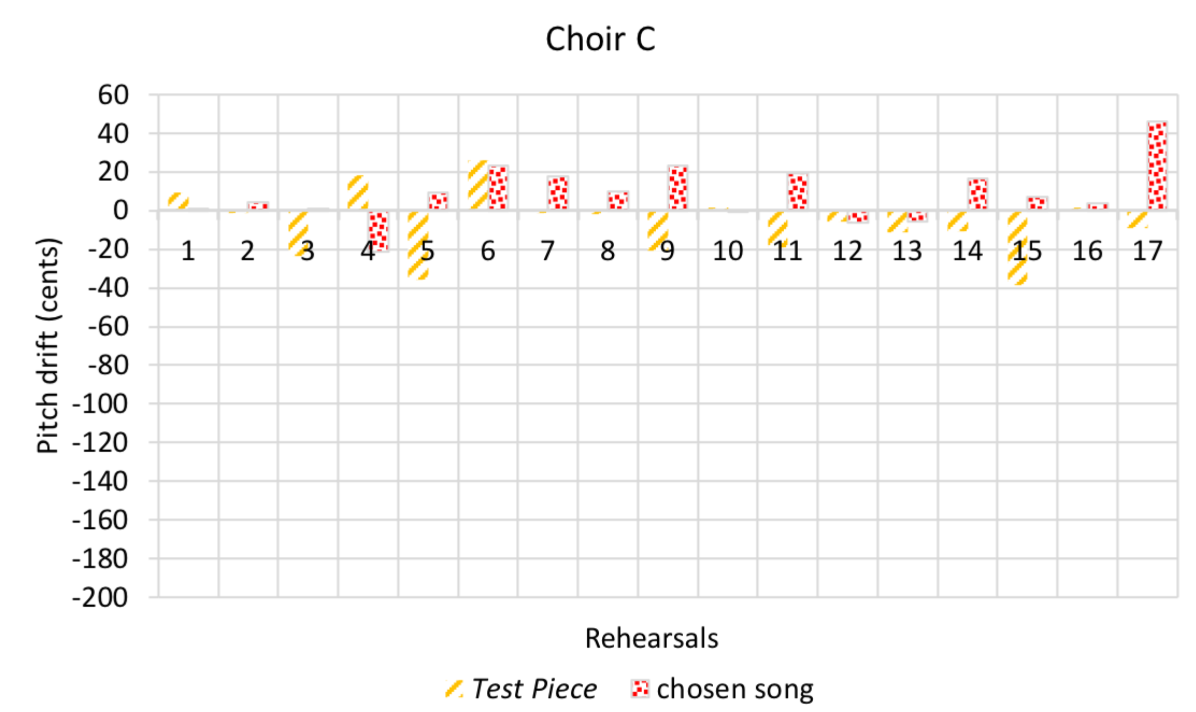
Choir K

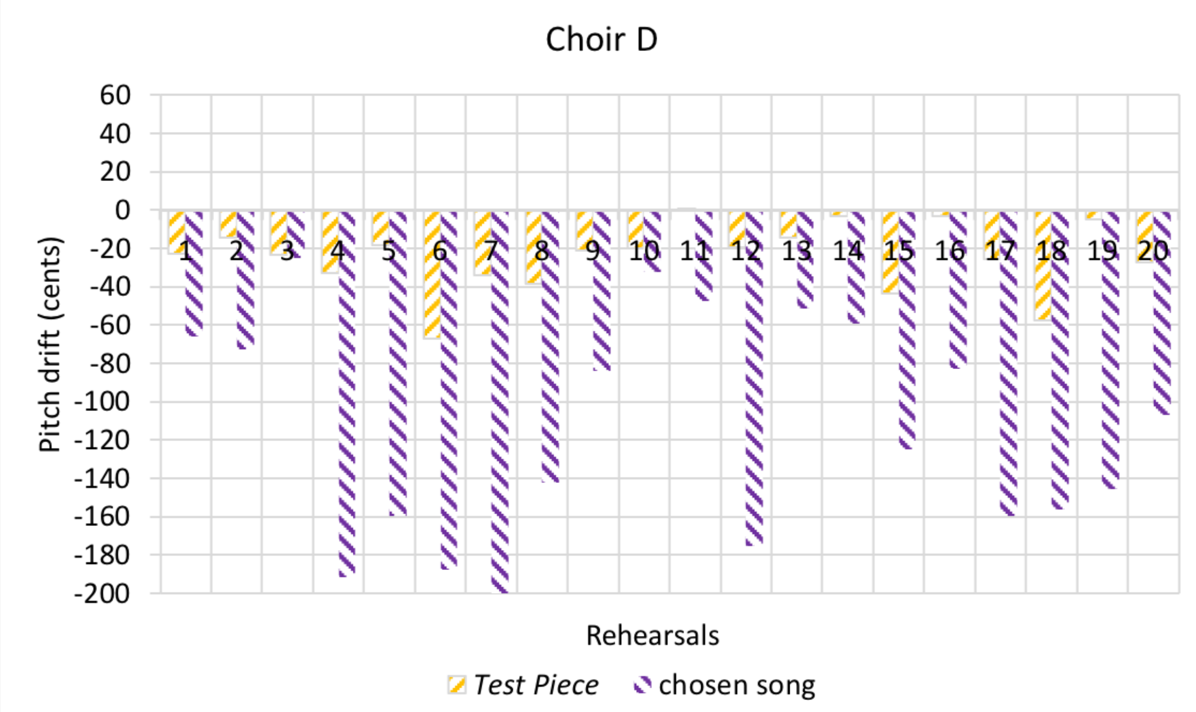
Test Piece												
Rehearsal	1	2	3	4	5	6	7	8	9	10	11	12
Quant	G	P	P	G	G	P	P	G	G	G	P	P
Qual1	G	G	P	P	P	P	P	G	G	G	P	P
Qual2	P	G	G	P	G	P	P	G	P	G	G	P
Pitch drift rating	**G**	**G**	**P**	**P**	**G**	**P**	**P**	**G**	**G**	**G**	**P**	**P**
Chosen song												
Rehearsal	1	2	3	4	5	6	7	8	9	10	11	12
Quant rating	G	G	P	P	G	G	P	G	P	G	P	G
Qual1 rating	G	G	P	G	G	G	P	G	P	G	P	G
Qual2 rating	G	G	P	P	G	G	P	G	G	G	P	G
Pitch drift rating	**G**	**G**	**P**	**P**	**G**	**G**	**P**	**G**	**P**	**G**	**P**	**G**

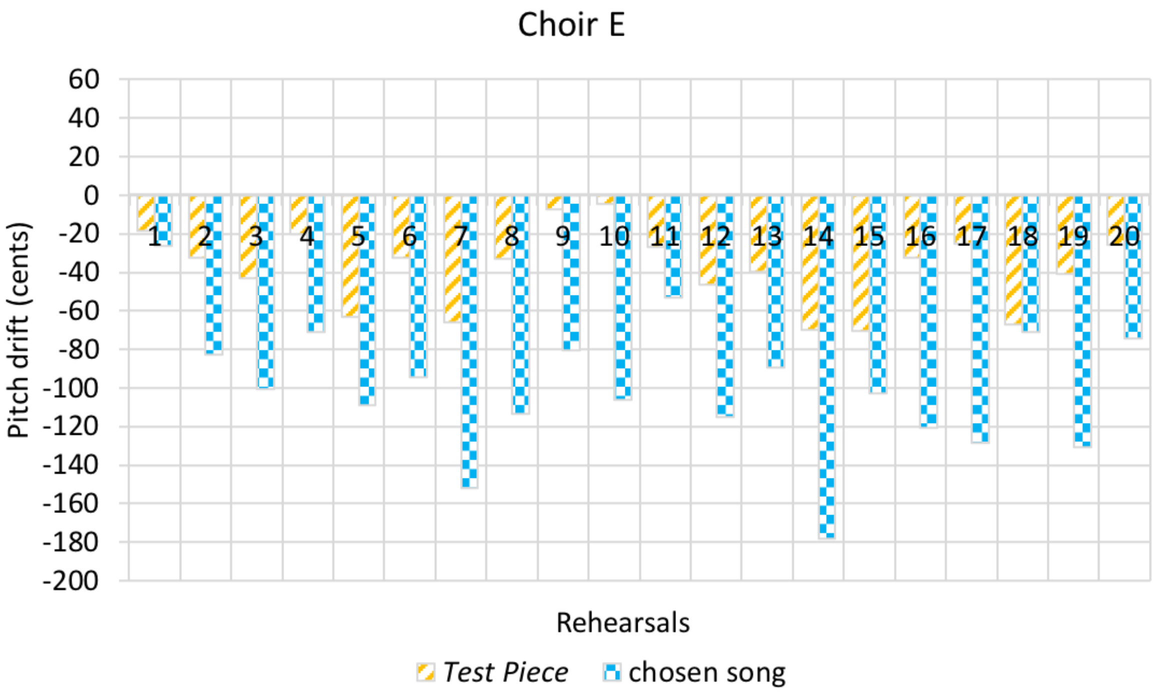
Appendix 15 Charts of pitch drift ratings



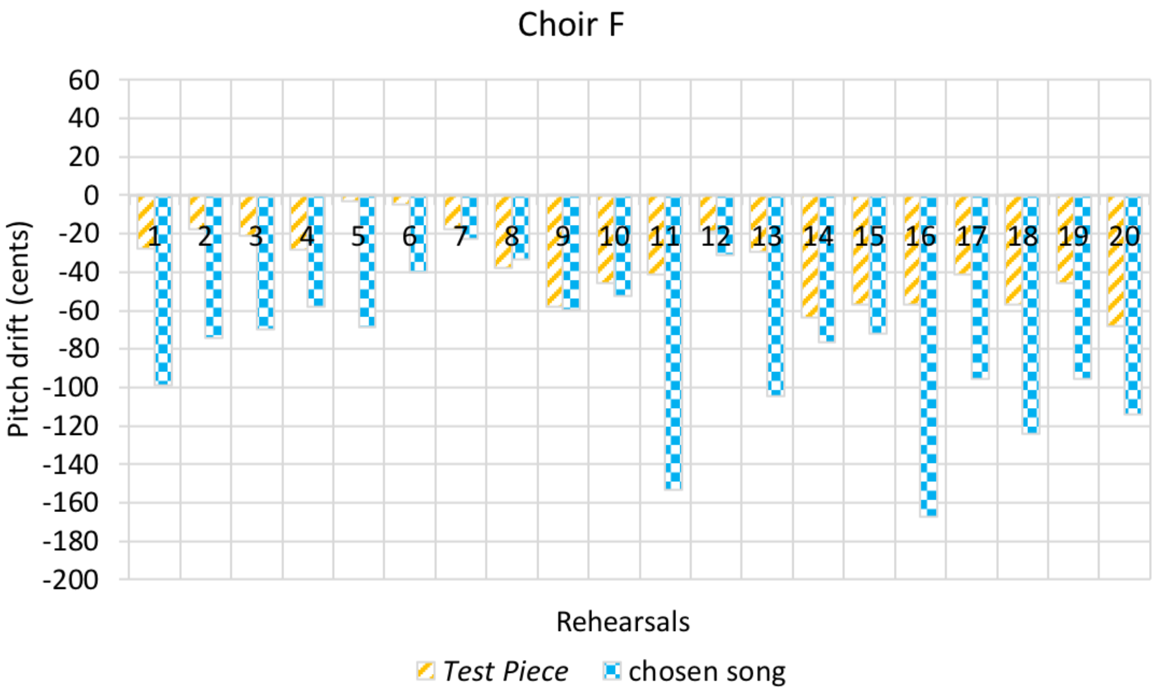



Choir C
60
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
Pitch drift (cents)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
Rehearsals
Test Piece
chosen song

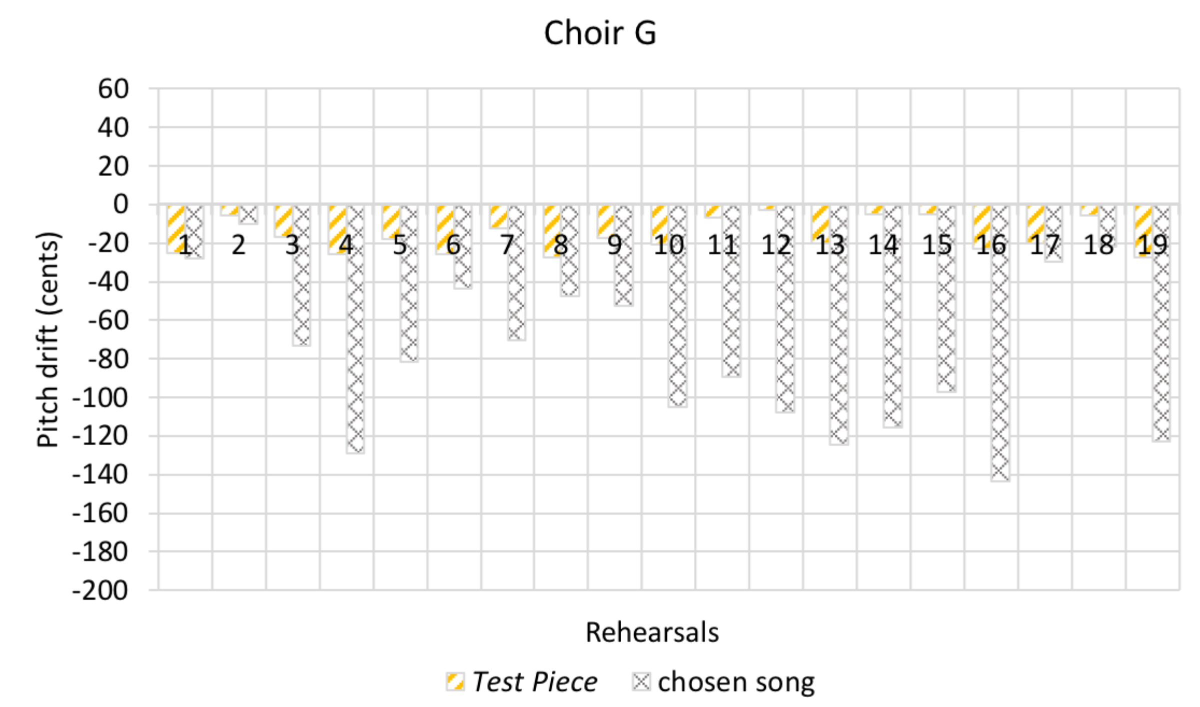

Choir D
60
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
Pitch drift (cents)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Rehearsals
Test Piece
chosen song

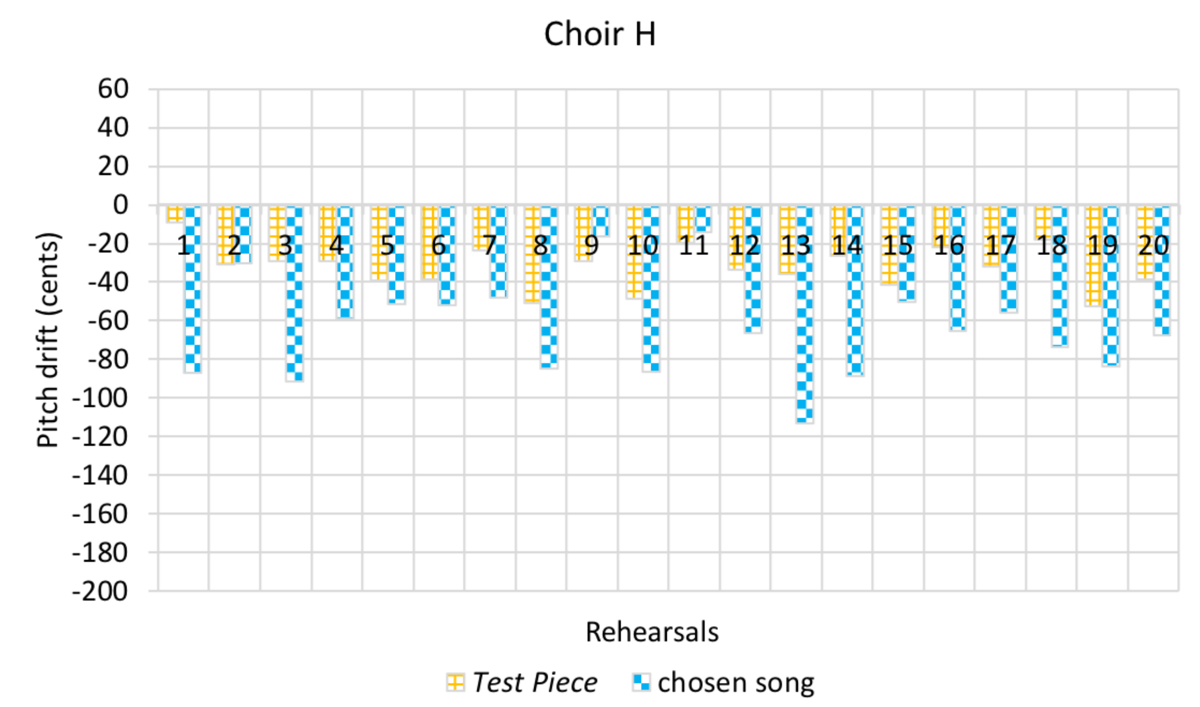


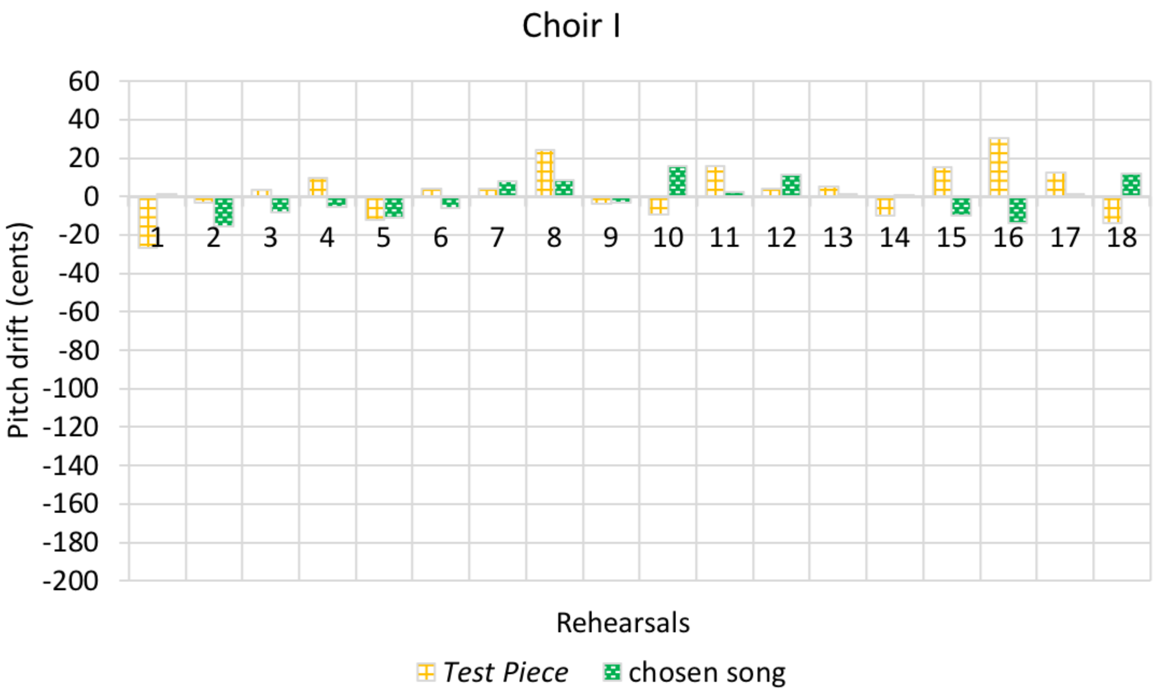
Choir E
Pitch drift (cents)
60
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Rehearsals
Test Piece
chosen song

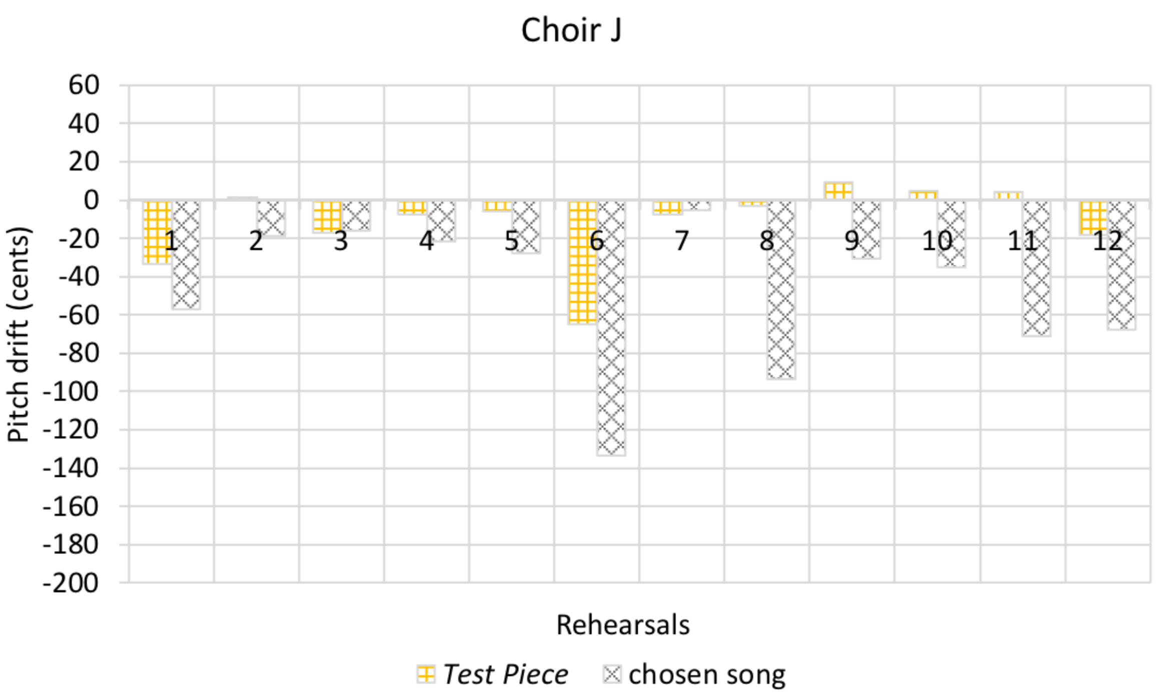


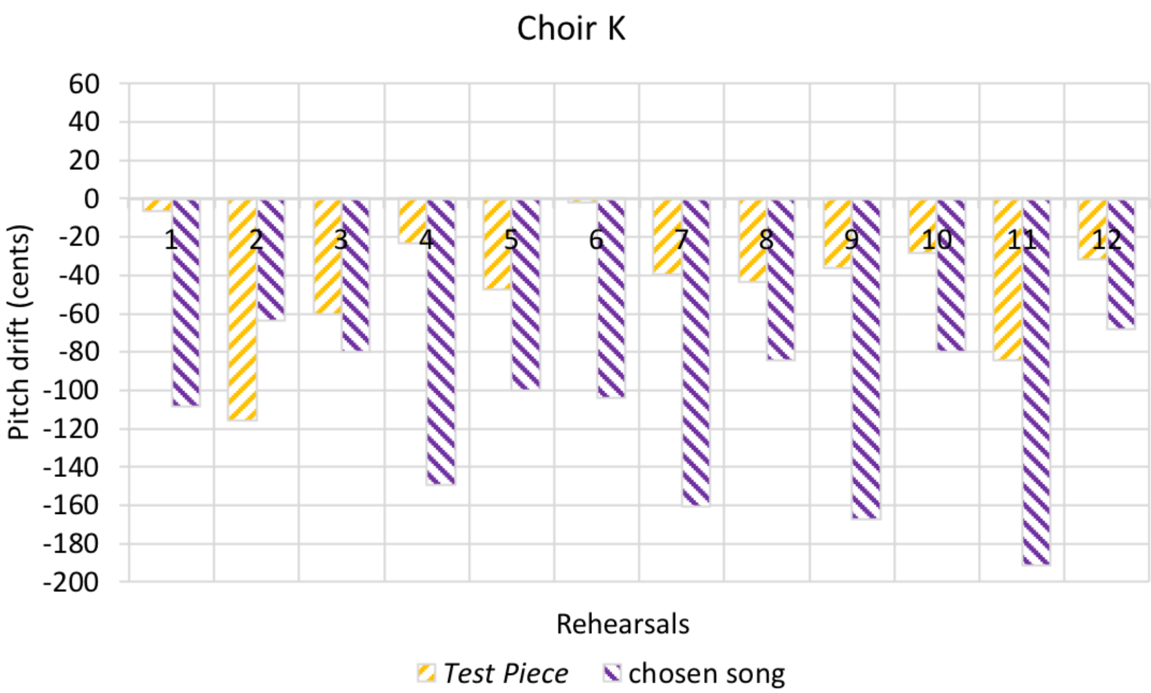
Choir F
Pitch drift (cents)
60
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Rehearsals
Test Piece
chosen song


Choir G
60
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
Pitch drift (cents)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
Rehearsals
Test Piece
chosen song


Choir H
60
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
Pitch drift (cents)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Rehearsals
Test Piece
chosen song


Choir I
60
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
Pitch drift (cents)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
Rehearsals
Test Piece
chosen song

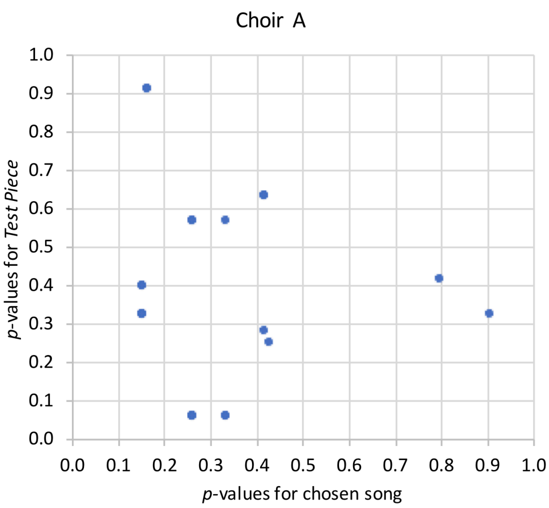

Choir J
60
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
Pitch drift (cents)
1 2 3 4 5 6 7 8 9 10 11 12
Rehearsals
Test Piece
chosen song


Choir K
60
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
-200
Pitch drift (cents)
1
2
3
4
5
6
7
8
9
10
11
12
Rehearsals
Test Piece
chosen song

Appendix 16 Statistical results attendance against pitch drift for each choir

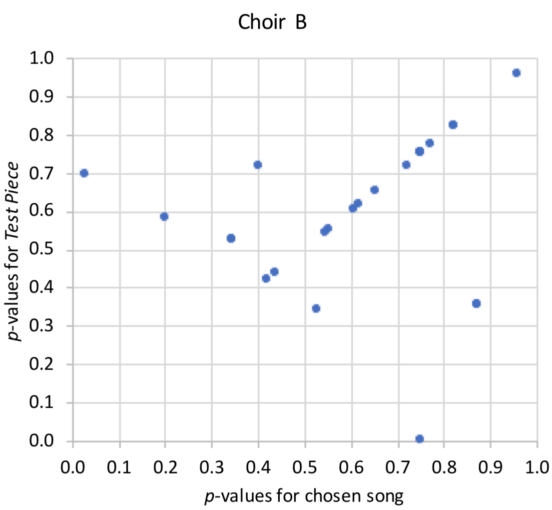
Choir A	*p Test Piece*	G/B	*p* chosen song	G/B	*p* Fisher	Attend
Singer A	0.326	0.538	0.155	-0.923	0.201	85%
Singer B	0.569	-0.231	0.335	-0.462	0.507	92%
Singer C	0.400	-0.462	0.155	-0.923	0.234	85%
Singer D	0.913	0.077	0.164	1.154	0.434	69%
Singer E	0.569	-0.231	0.261	0.538	0.431	92%
Singer F	0.057	0.769	0.335	-0.462	0.095	92%
Singer G	0.631	0.308	0.416	0.615	0.614	77%
Singer I	0.326	0.538	0.155	-0.923	0.201	85%
Singer J	0.400	0.462	0.155	0.923	0.234	15%
Singer K	0.252	0.846	0.429	0.692	0.349	62%
Singer L	0.326	0.538	0.906	0.077	0.655	85%
Singer M	0.279	-0.692	0.416	0.615	0.367	77%
Singer N	0.057	0.769	0.335	-0.462	0.095	92%
Singer O	0.057	0.769	0.261	0.538	0.078	92%
Singer P	0.913	0.077	0.164	1.154	0.434	69%
Singer S	0.326	0.538	0.155	-0.923	0.201	85%
Singer T	0.631	0.308	0.416	0.615	0.614	77%
Singer W	0.057	0.769	0.261	0.538	0.078	92%
Singer X	0.569	-0.231	0.261	0.538	0.431	92%
Singer Y	0.057	0.769	0.261	0.538	0.078	92%
Singer Z	0.416	0.615	0.797	0.231	0.698	54%

Total of 26 singers but 5 had 100% attendance



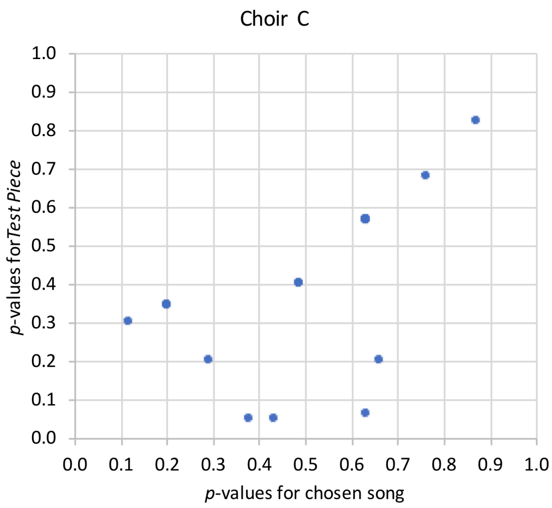
Choir B	*p Test Piece*	G/B	*p* chosen song	G/B	*p* Fisher	Attend
Singer A	0.655	0.200	0.655	0.200	0.792	20%
Singer B	0.357	0.850	0.871	-0.150	0.674	85%
Singer C	0.823	0.050	0.823	0.050	0.941	5%
Singer D	0.699	0.150	0.028	-0.850	0.097	15%
Singer E	0.617	0.250	0.617	0.250	0.748	25%
Singer F	0.004	-0.900	0.752	0.100	0.022	10%
Singer G	0.554	0.350	0.554	0.350	0.670	35%
Singer H	0.439	0.600	0.439	0.600	0.509	60%
Singer I	0.959	-0.050	0.959	-0.050	0.997	95%
Singer J	0.606	-0.400	0.606	-0.400	0.735	60%
Singer K	0.527	0.400	0.343	-0.600	0.490	40%
Singer L	0.420	0.650	0.420	0.650	0.483	65%
Singer M	0.752	0.100	0.752	0.100	0.888	10%
Singer N	0.823	0.050	0.823	0.050	0.941	5%
Singer O	0.752	0.100	0.752	0.100	0.888	10%
Singer P	0.584	0.300	0.201	-0.700	0.369	30%
Singer Q	0.527	0.400	0.343	-0.600	0.490	40%
Singer R	0.357	0.850	0.871	-0.150	0.674	85%
Singer T	0.343	-0.600	0.527	0.400	0.490	40%
Singer U	0.720	-0.300	0.403	0.700	0.649	70%
Singer V	0.752	0.100	0.752	0.100	0.888	10%
Singer W	0.720	-0.300	0.720	-0.300	0.859	70%
Singer X	0.544	-0.450	0.544	-0.450	0.656	55%
Singer Y	0.773	-0.250	0.773	-0.250	0.905	75%

Total of 25 singers but 1 had 100% attendance



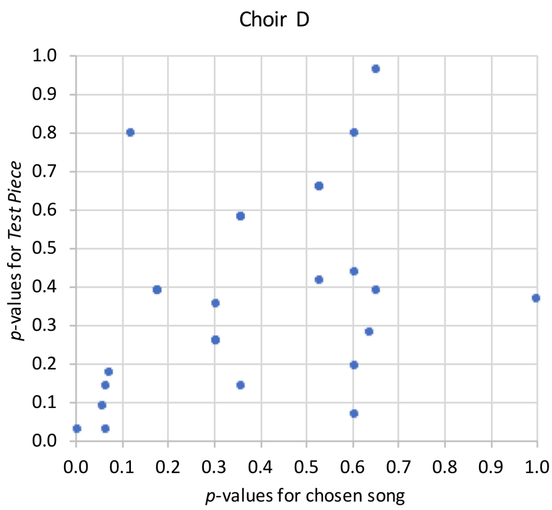
Choir C	*p Test Piece*	G/B	*p* chosen song	G/B	*p* Fisher	Attend
Singer A	0.404	-0.471	0.486	-0.353	0.516	88%
Singer B	0.682	0.353	0.761	-0.235	0.859	59%
Singer C	0.567	-0.235	0.633	-0.176	0.727	94%
Singer D	0.205	-0.941	0.290	-0.706	0.227	76%
Singer E	0.567	-0.235	0.633	-0.176	0.727	94%
Singer G	0.567	-0.235	0.633	-0.176	0.727	94%
Singer H	0.052	1.294	0.377	-0.529	0.097	82%
Singer I	0.567	-0.235	0.633	-0.176	0.727	94%
Singer K	0.347	0.529	0.201	0.647	0.256	88%
Singer L	0.567	-0.235	0.633	-0.176	0.727	94%
Singer M	0.052	1.294	0.432	0.471	0.435	82%
Singer N	0.063	0.765	0.633	-0.176	0.727	94%
Singer P	0.347	0.529	0.201	0.647	0.068	88%
Singer R	0.347	0.529	0.201	0.647	0.256	88%
Singer S	0.567	-0.235	0.633	-0.176	0.553	94%
Singer T	0.404	-0.471	0.486	-0.353	0.469	88%
Singer U	0.205	-0.941	0.659	0.294	0.742	76%
Singer V	0.301	-0.824	0.119	-1.118	0.193	29%
Singer W	0.825	-0.176	0.870	0.118	0.485	71%

Total of 23 singers but 4 had 100% attendance



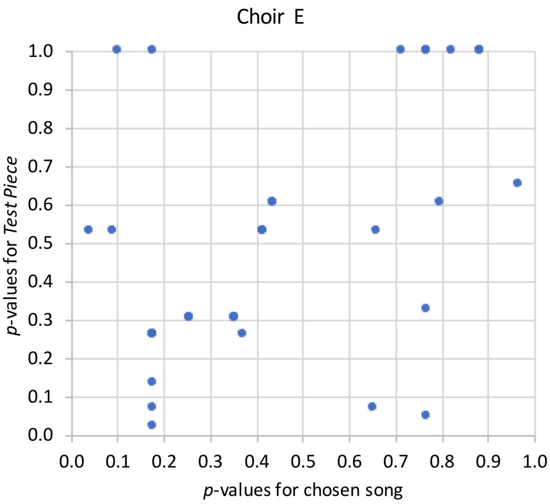
Choir D	*p Test Piece*	G/B	*p* chosen song	G/B	*p* Fisher	Attend
Singer A	0.028	2.400	0.068	2.000	0.014	60%
Singer B	0.795	-0.250	0.606	-0.500	0.833	75%
Singer C	0.194	-1.250	0.606	-0.500	0.370	75%
Singer D	0.391	0.950	0.653	-0.500	0.604	55%
Singer E	0.178	-1.500	0.074	-2.000	0.070	50%
Singer F	0.436	0.750	0.606	0.500	0.616	75%
Singer G	0.257	0.550	0.305	0.500	0.278	95%
Singer H	0.391	0.950	0.178	1.500	0.254	55%
Singer I	0.142	-1.600	0.068	-2.000	0.054	60%
Singer J	0.257	-0.550	0.305	-0.500	0.278	5%
Singer K	0.660	-0.350	0.531	-0.500	0.718	85%
Singer L	0.353	-0.450	0.305	-0.500	0.348	95%
Singer N	0.089	1.350	0.060	1.500	0.033	15%
Singer O	0.369	-0.800	1.000	0.000	0.737	80%
Singer P	0.413	0.650	0.531	0.500	0.552	85%
Singer Q	0.028	2.400	0.006	3.000	0.002	60%
Singer R	0.279	1.150	0.639	0.500	0.485	35%
Singer S	0.660	0.350	0.531	0.500	0.718	15%
Singer T	0.582	-0.600	0.361	-1.000	0.538	60%
Singer U	0.964	0.050	0.653	-0.500	0.921	45%
Singer V	0.391	0.950	0.178	1.500	0.254	55%
Singer W	0.142	1.600	0.361	1.000	0.204	40%
Singer X	0.069	1.750	0.606	0.500	0.175	75%
Singer Y	0.795	-0.250	0.121	-1.500	0.322	75%
Singer Z	0.582	0.600	0.361	1.000	0.538	40%

Total of 26 singers but 1 had 100% attendance



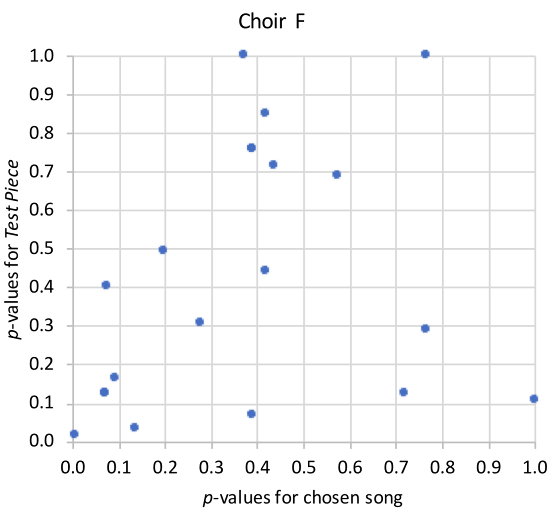
Choir E	*p Test Piece*	G/B	*p* chosen song	G/B	*p* Fisher	Attend
Singer A	*0.531*	-0.500	*0.038*	-1.650	*0.099*	85%
Singer B	*0.074*	-2.000	*0.178*	-1.500	*0.070*	50%
Singer C	*0.653*	-0.500	*0.964*	0.050	*0.921*	55%
Singer D	*0.606*	-0.500	*0.795*	0.250	*0.833*	75%
Singer E	*0.264*	-1.000	*0.178*	-1.200	*0.190*	80%
Singer F	*1.000*	0.000	*0.178*	-1.200	*0.484*	80%
Singer G	*0.051*	-2.000	*0.769*	-0.300	*0.166*	70%
Singer H	*1.000*	0.000	*0.881*	-0.100	*0.993*	90%
Singer I	*0.264*	1.000	*0.369*	0.800	*0.324*	80%
Singer J	*1.000*	0.000	*0.714*	-0.400	*0.954*	60%
Singer K	*0.531*	0.500	*0.413*	0.650	*0.552*	15%
Singer L	*0.305*	-0.500	*0.257*	0.550	*0.278*	5%
Singer M	*0.074*	2.000	*0.653*	0.500	*0.194*	50%
Singer N	*1.000*	0.000	*0.769*	-0.300	*0.971*	70%
Singer O	*0.329*	-1.000	*0.769*	-0.300	*0.601*	70%
Singer P	*1.000*	0.000	*0.769*	-0.300	*0.971*	70%
Singer R	*0.264*	1.000	*0.178*	1.200	*0.190*	20%
Singer S	*0.531*	-0.500	*0.660*	0.350	*0.718*	85%
Singer T	*0.531*	-0.500	*0.413*	-0.650	*0.552*	85%
Singer U	*0.305*	-0.500	*0.353*	0.450	*0.348*	95%
Singer W	*0.305*	0.500	*0.353*	0.450	*0.348*	95%
Singer X	*0.305*	0.500	*0.257*	0.550	*0.278*	5%
Singer Y	*1.000*	0.000	*0.822*	-0.200	*0.983*	80%
Singer Z	*0.264*	-1.000	*0.178*	-1.200	*0.190*	80%
Singer AA	*0.305*	-0.500	*0.353*	-0.450	*0.348*	5%
Singer AB	*0.531*	0.500	*0.089*	1.350	*0.192*	85%
Singer AC	*0.606*	0.500	*0.436*	0.750	*0.616*	25%
Singer AD	*0.606*	-0.500	*0.436*	-0.750	*0.616*	75%
Singer AE	*0.025*	-2.000	*0.178*	-1.200	*0.029*	80%
Singer AF	*1.000*	0.000	*0.881*	0.100	*0.993*	10%
Singer AG	*0.136*	-1.000	*0.178*	0.900	*0.114*	90%
Singer AH	*1.000*	0.000	*0.099*	-1.100	*0.329*	90%

Total of 34 singers but 2 had 100% attendance



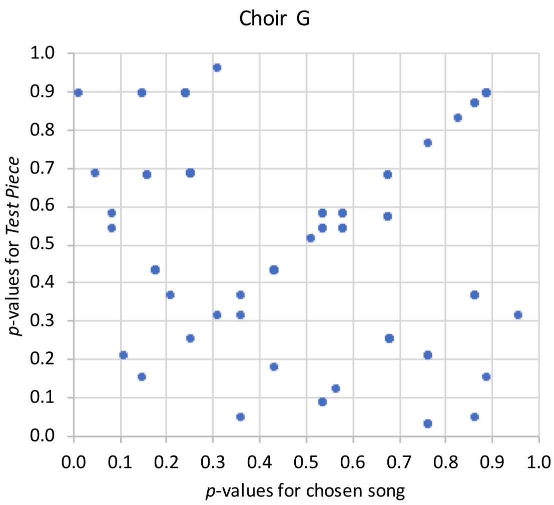
Choir F	*p Test Piece*	G/B	*p* chosen song	G/B	*p* Fisher	Attend
Singer A	*0.402*	-0.400	*0.076*	-0.750	*0.137*	95%
Singer B	*0.110*	1.400	*1.000*	0.000	*0.353*	80%
Singer C	*0.292*	-1.000	*0.766*	0.250	*0.558*	75%
Singer D	*0.848*	0.200	*0.417*	0.750	*0.721*	65%
Singer E	*0.125*	-1.200	*0.718*	-0.250	*0.306*	85%
Singer F	*0.306*	0.800	*0.278*	0.750	*0.295*	85%
Singer G	*0.125*	-1.200	*0.071*	-1.250	*0.051*	85%
Singer H	*0.761*	0.200	*0.389*	0.500	*0.657*	90%
Singer I	*0.690*	-0.400	*0.573*	0.500	*0.763*	70%
Singer J	*0.017*	-2.400	*0.005*	-2.500	*0.001*	70%
Singer K	*0.068*	1.200	*0.389*	0.500	*0.040*	90%
Singer L	*0.761*	0.200	*0.389*	-0.500	*0.122*	90%
Singer M	*0.125*	-1.200	*0.071*	-1.250	*0.211*	85%
Singer N	*0.494*	-0.600	*0.197*	-1.000	*0.116*	80%
Singer O	*0.714*	0.400	*0.436*	-0.750	*0.546*	55%
Singer Q	*0.444*	-0.800	*0.417*	0.750	*0.658*	65%
Singer R	*1.000*	0.000	*0.371*	-0.750	*0.462*	75%
Singer S	*0.035*	2.000	*0.136*	1.250	*0.407*	75%
Singer T	*0.163*	-1.400	*0.091*	-1.500	*0.021*	70%
Singer U	*1.000*	0.000	*0.766*	0.250	*0.385*	75%

Total of 21 singers but 1 had 100% attendance



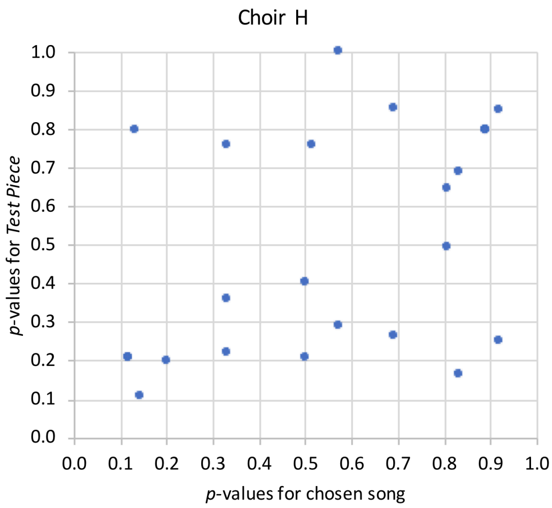
Choir G	*p Test Piece*	G/B	*p* chosen song	G/B	*p* Fisher	Attend
Singer A	0.086	-1.474	0.539	-0.526	0.188	79%
Singer B	0.891	0.105	0.891	-0.105	0.977	16%
Singer C	0.891	-0.105	0.243	-0.895	0.548	84%
Singer D	0.433	-0.368	0.433	0.368	0.501	95%
Singer E	0.764	-0.316	0.764	0.316	0.898	53%
Singer F	0.581	-0.474	0.539	-0.526	0.777	79%
Singer G	0.311	1.053	0.960	-0.053	0.883	58%
Singer H	0.683	0.263	0.253	0.737	0.279	89%
Singer I	0.433	-0.368	0.433	0.368	0.656	95%
Singer J	0.865	0.158	0.865	-0.158	0.742	74%
Singer K	0.568	0.579	0.678	0.421	0.899	37%
Singer L	0.539	0.526	0.539	-0.526	0.669	79%
Singer M	0.433	-0.368	0.179	-0.632	0.322	95%
Singer N	0.683	0.263	0.253	0.737	0.352	89%
Singer O	0.027	2.316	0.764	-0.316	0.861	47%
Singer Q	0.581	-0.474	0.086	1.474	0.017	79%
Singer R	0.568	-0.579	0.678	-0.421	0.761	63%
Singer S	0.539	0.526	0.539	-0.526	0.669	79%
Singer T	0.539	0.526	0.581	0.474	0.677	79%
Singer U	0.253	-0.737	0.253	0.737	0.409	89%
Singer V	0.363	-0.842	0.865	-0.158	0.552	74%
Singer W	0.891	-0.105	0.891	0.105	0.689	84%
Singer X	0.960	0.053	0.311	-1.053	0.632	58%
Singer Y	0.539	0.526	0.086	1.474	0.287	79%
Singer Z	0.311	-1.053	0.311	1.053	0.467	42%
Singer AA	0.581	-0.474	0.539	-0.526	0.467	79%
Singer AC	0.047	-1.842	0.865	-0.158	0.848	74%
Singer AD	0.120	-1.579	0.568	0.579	0.123	63%
Singer AE	0.086	-1.474	0.539	-0.526	0.241	79%
Singer AF	0.363	-0.842	0.211	-1.158	0.091	74%
Singer AG	0.581	-0.474	0.581	0.474	0.539	79%
Singer AH	0.829	-0.211	0.829	0.211	0.833	68%
Singer AI	0.683	0.263	0.050	-1.263	0.174	89%
Singer AJ	0.865	0.158	0.865	-0.158	0.902	74%
Singer AK	0.683	0.263	0.253	0.737	0.552	89%
Singer AL	0.433	-0.368	0.179	-0.632	0.379	95%
Singer AM	0.515	0.684	0.515	-0.684	0.557	53%
Singer AN	0.149	-1.105	0.891	0.105	0.816	84%
Singer AO	0.678	-0.421	0.161	1.421	0.114	37%
Singer AP	0.210	1.316	0.764	-0.316	0.859	47%
Singer AQ	0.891	0.105	0.891	-0.105	0.501	16%
Singer AR	0.678	-0.421	0.678	0.421	0.909	37%
Singer AS	0.363	-0.842	0.865	-0.158	0.899	74%
Singer AT	0.149	-1.105	0.149	1.105	0.212	84%
Singer AU	0.678	0.421	0.161	-1.421	0.114	63%
Singer AW	0.210	-1.316	0.764	0.316	0.859	53%
Singer AX	0.433	-0.368	0.179	-0.632	0.161	95%
Singer AZ	0.683	0.263	0.253	0.737	0.352	89%
Singer BA	0.433	-0.368	0.433	0.368	0.656	95%
Singer BB	0.253	-0.737	0.683	-0.263	0.656	89%
Singer BC	0.891	-0.105	0.149	1.105	0.162	84%
Singer BD	0.891	-0.105	0.243	-0.895	0.464	84%
Singer BE	0.678	0.421	0.678	-0.421	0.653	63%
Singer BF	0.210	-1.316	0.109	-1.684	0.126	53%
Singer BG	0.891	-0.105	0.243	-0.895	0.548	84%
Singer BH	0.027	2.316	0.764	-0.316	0.942	47%
Singer BI	0.311	-1.053	0.361	-0.947	0.590	42%
Singer BJ	0.539	0.526	0.581	0.474	0.379	79%
Singer BK	0.433	0.368	0.433	-0.368	0.753	5%
Singer BL	0.891	-0.105	0.149	1.105	0.027	84%
Singer BM	0.253	-0.737	0.683	-0.263	0.541	89%
Singer BN	0.581	-0.474	0.581	0.474	0.677	79%
Singer BO	0.179	0.632	0.433	0.368	0.501	95%
Singer BP	0.047	-1.842	0.363	0.842	0.689	74%
Singer BQ	0.253	-0.737	0.683	-0.263	0.477	89%
Singer BR	0.363	-0.842	0.363	0.842	0.539	74%
Singer BS	0.891	-0.105	0.013	-1.895	0.017	84%

Total of 71 singers but 4 had 100% attendance



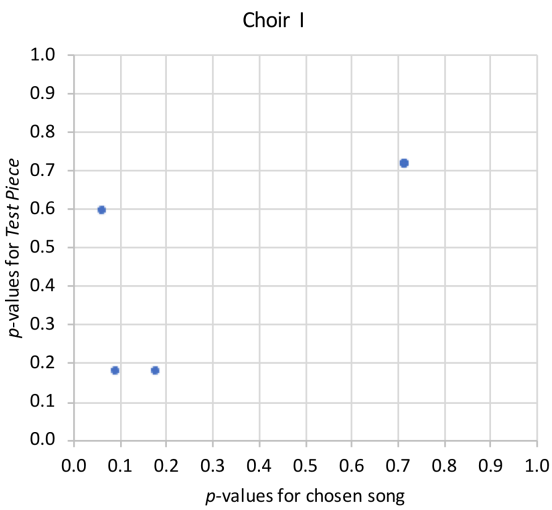
Choir H	*p Test Piece*	G/B	*p* chosen song	G/B	*p* Fisher	Attend
Singer A	0.761	0.200	0.515	0.400	0.759	10%
Singer B	0.251	-1.200	0.919	0.100	0.569	65%
Singer C	0.209	-0.600	0.117	-0.700	0.115	95%
Singer D	0.163	1.400	0.831	-0.200	0.407	70%
Singer E	0.852	-0.200	0.690	-0.400	0.900	40%
Singer F	0.690	0.400	0.831	-0.200	0.893	70%
Singer G	0.209	-0.600	0.117	-0.700	0.115	95%
Singer H	0.761	-0.200	0.329	0.600	0.597	90%
Singer I	0.264	-1.200	0.690	-0.400	0.492	40%
Singer J	0.209	-0.600	0.502	0.300	0.341	95%
Singer K	0.494	0.600	0.807	0.200	0.765	80%
Singer L	0.361	1.000	0.329	1.000	0.372	50%
Singer M	0.798	0.200	0.133	-1.100	0.344	85%
Singer N	0.648	-0.400	0.807	0.200	0.862	80%
Singer O	0.798	-0.200	0.891	0.100	0.954	15%
Singer P	0.199	1.400	0.202	1.300	0.170	45%
Singer Q	0.292	1.000	0.573	-0.500	0.466	75%
Singer R	0.798	0.200	0.891	-0.100	0.954	85%
Singer S	0.110	-1.400	0.143	1.200	0.081	80%
Singer T	0.798	0.200	0.891	-0.100	0.326	85%
Singer U	0.224	0.800	0.329	0.600	0.614	90%
Singer V	1.000	0.000	0.573	0.500	0.391	25%
Singer W	0.848	-0.200	0.919	0.100	0.997	65%
Singer X	0.402	0.400	0.502	0.300	0.789	95%

Total of 25 singers but 1 had 100% attendance



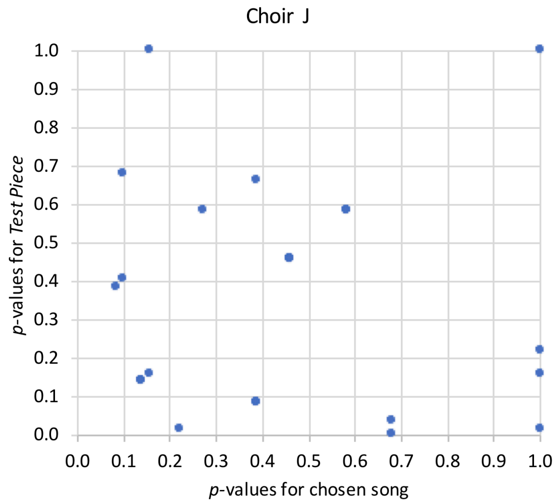
Choir I	*p Test Piece*	G/B	*p* chosen song	G/B	*p* Fisher	Attend
Singer A	0.180	0.889	0.094	-1.111	0.085	44%
Singer B	0.596	-0.222	0.063	0.778	0.162	89%
Singer C	0.716	-0.111	0.716	-0.111	0.855	94%
Singer E	0.716	-0.111	0.716	-0.111	0.855	94%
Singer G	0.716	-0.111	0.716	-0.111	0.855	94%
Singer H	0.180	-0.667	0.180	-0.667	0.143	17%

Total of 8 singers but 2 had 100% attendance



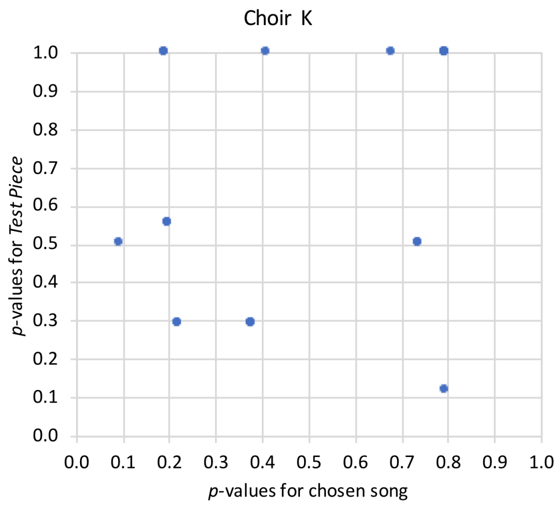
Choir J	*p Test Piece*	G/B	*p* chosen song	G/B	*p* Fisher	Attend
Singer A	*0.460*	-2.000	*0.460*	-1.000	*0.540*	50%
Singer B	*0.221*	0.333	*1.000*	0.333	*0.554*	83%
Singer C	*0.584*	1.000	*0.584*	0.000	*0.708*	75%
Singer D	*0.157*	0.333	*1.000*	0.333	*0.448*	83%
Singer E	*1.000*	0.667	*1.000*	-1.333	*1.000*	42%
Singer F	*0.386*	0.667	*0.083*	0.667	*0.143*	92%
Singer G	*0.140*	-0.333	*0.140*	-0.333	*0.096*	92%
Singer H	*0.460*	0.000	*0.460*	0.000	*0.540*	75%
Singer I	*0.679*	0.667	*0.098*	0.667	*0.246*	92%
Singer K	*0.408*	-0.333	*0.098*	0.667	*0.168*	67%
Singer L	*0.665*	1.000	*0.386*	-1.000	*0.606*	75%
Singer M	*0.014*	0.000	*0.221*	1.000	*0.021*	75%
Singer N	*1.000*	-0.333	*0.157*	-0.333	*0.448*	92%
Singer P	*0.460*	-1.000	*0.460*	0.000	*0.540*	50%
Singer Q	*0.584*	0.333	*0.584*	-0.667	*0.708*	83%
Singer R	*0.140*	0.667	*0.140*	-1.333	*0.096*	67%
Singer_S	*0.014*	-0.333	*1.000*	-0.333	*0.075*	92%
Singer U	*0.038*	1.333	*0.679*	-0.667	*0.121*	33%
Singer V	*0.157*	2.333	*0.157*	0.333	*0.116*	58%
Singer W	*0.584*	-1.667	*0.273*	0.333	*0.452*	58%
Singer X	*0.004*	2.000	*0.679*	0.000	*0.018*	50%
Singer Y	*0.083*	2.000	*0.386*	0.000	*0.143*	50%
Singer Z	*0.083*	-0.333	*0.386*	-1.333	*0.143*	42%

Total of 26 singers but 3 had 100% attendance



Choir K	*p Test Piece*	G/B	*p* chosen song	G/B	*p* Fisher	Attend
Singer A	*0.296*	-0.500	*0.217*	0.583	*0.240*	92%
Singer B	*0.505*	-0.500	*0.091*	-1.250	*0.187*	75%
Singer C	*0.505*	-0.500	*0.735*	0.250	*0.739*	25%
Singer E	*0.296*	0.500	*0.217*	0.583	*0.240*	92%
Singer F	*0.296*	-0.500	*0.377*	-0.417	*0.357*	92%
Singer G	*1.000*	0.000	*0.190*	-0.833	*0.506*	83%
Singer H	*1.000*	0.000	*0.408*	-0.667	*0.773*	67%
Singer I	*1.000*	0.000	*0.793*	0.167	*0.977*	83%
Singer K	*0.558*	0.500	*0.198*	-1.083	*0.354*	58%
Singer L	*1.000*	0.000	*0.793*	0.167	*0.977*	83%
Singer M	*1.000*	0.000	*0.793*	0.167	*0.977*	83%
Singer N	*0.296*	0.500	*0.377*	-0.417	*0.357*	92%
Singer O	*0.121*	1.000	*0.793*	0.167	*0.322*	83%
Singer P	*1.000*	0.000	*0.190*	-0.833	*0.506*	83%
Singer Q	*0.296*	0.500	*0.377*	-0.417	*0.357*	92%
Singer S	*0.558*	-0.500	*0.198*	-1.083	*0.354*	58%
Singer T	*1.000*	0.000	*0.793*	0.167	*0.977*	83%
Singer U	*0.505*	-0.500	*0.735*	0.250	*0.739*	25%
Singer V	*1.000*	0.000	*0.679*	0.333	*0.942*	67%

Total of 22 singers but 3 had 100% attendance



Appendix 17 Choirs taking part in the research

Listed below in alphabetical order are the choirs who took part in the research in 2015/16.

Choir name	Musical Director	Location
Circle Singers	Peter Sheppard	Royal Leamington Spa
Clifton Singers	Nick Barlow	Bristol
Consensus	Allan Leroy	Northampton
Divertimento	Sheila Koch	Royal Leamington Spa
Linsdale Singers	Dennis Pim	Leighton Buzzard
MK Acapella	Lyn Kidby	Milton Keynes
The Open University Choir	Bill Strang	Milton Keynes
Sherwood Choral Society	Richard Heyes	Bletchley
Sine Nomine	Ben Miller	Norwich
Solent	Vincent Iyengar	Portsmouth
St Mary's Church Choir	Tim Smith	Harrow-on-the-Hill